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Evaluating the association between heatwave vulnerability index and related deaths in Australia

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ABSTRACT

Heatwaves affect public health. Previous human heat vulnerability assessment studies, mostly focused in urban areas, suggest association with heat-related deaths. However, these associations have not been thoroughly examined in Australia. We examined the association between heatwave vulnerability index (HVI) and risk of heatwave-related deaths across Australia.

Seasonal (December–February) all-cause mortality and heatwave data across 2189 Statistical Area Level 2 (SA2s) spatial units were acquired from 2001 to 2019. We also used SA2 level heatwave vulnerability index (HVI) data estimated from 2021 national census data and heatwave data (2001–2019) across Australia. In each SA2, we calculated seasonal mortality rates using the empirical Bayes smoothing approach to account for spatial variations in deaths. We then used a quasi-Poisson regression model to quantify the mortality rates associated with SA2-specific heatwave days across Australia. Finally, we used a linear regression analysis to examine the association between HVI and heatwave-related deaths. We observed an association between HVI (β: 0.18, 95 % CI: 0.08–0.27) and increased in percentage (%) of heatwave-related deaths across the capital cities. A unit increase in HVI -associated deaths was higher under severe heatwave days (β: 0.39, 95 % CI: 0.05–0.74) compared to low-intensity heatwave days (β: 0.21, 95 % CI: 0.09–0.32). We also found that the HVI component factor formed by low education, low income, low healthcare professionals, and diabetes prevalence is strongly associated with all the heatwave-related deaths in the capital cities. In an Australia-wide analysis, we did not find an association (β: -0.06, CI: −0.17-0.05) between HVI and risk of heatwave-related death. However, there was evidence of stronger association between HVI component factor formed by Indigenous population exposed to longer heatwave days and increased % of heatwave-associated deaths. HVI is positively associated with heatwave-related deaths in Australia, particularly in capital cities. Heatwave management strategies should include HVI maps to help protect communities against heatwave-related death, and morbidity.

1. Introduction

Risk of death from heatwave is increasing globally because of climate change (Chen et al., 2022; Lüthi et al., 2023; Mitchell et al., 2016; Vicedo-Cabrera et al., 2021). Many studies have reported increasing human vulnerability to extreme heat in urban areas (Conlon et al., 2020; Grigorescu et al., 2021; Inostroza et al., 2016; Manware et al., 2022; Reid et al., 2009). The reason is that urban areas or cities are generally characterized by urban heat island (UHI) effect, and higher population density (Hsu et al., 2021). Although UHI has been recognized as a major

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concern in urban areas, vulnerability is not limited to only heat exposure but also depends on the population's sensitivity, hazard, and adaptive capacity (Bao et al., 2015; Estoque et al., 2023). Non-urban areas with high heat vulnerability could also be susceptible to heat-related deaths due to limited adaptive capacities (e.g., limited accessibility to health-care services), and high sensitivity (e.g., poverty).

Several studies have examined the association between heatwave vulnerability index, and heat-related mortality and morbidity mainly in urban areas (Kamal et al., 2021; Maier et al., 2014; Rosenthal et al., 2014). Supporting the current notion that the potential of heat vulnerability index in predicting heatwave-related health outcomes is limited only to urban settings (Chen et al., 2016; Lee et al., 2022).

The findings on the association between HVI and heat-related deaths, and morbidity have remained inconsistent. In the United States, although spatial heat vulnerability was determined nationwide, the evidence of the association between heat vulnerability index, and an increase in hospital admissions and deaths was determined among some selected urbanized States (Reid et al., 2012). In Detroit City, a supervised heat vulnerability index could predict all-cause mortality at the Census tract level compared to an unsupervised vulnerability index (Conlon et al., 2020). In Brazil, univariant (coefficient value of 0.08) analysis showed a weaker relationship between heat vulnerability index, and heat-related deaths (Prosdocimi and Klima, 2020). In greater London, the heat vulnerability index could predict an increase in ambulance call-outs and mortality during heatwave days (Wolf et al., 2014). A study conducted across 95 counties in China obtained mixed results, while the overall heat vulnerability index was positively correlated with a heat-related attributable fraction of all-cause mortality, the association was found negative in urbanized areas (Wang et al., 2021).

In Australia, the knowledge about human heat vulnerability has been limited predominantly in urban settings, and some few selected geographical areas. The previous studies have not examined the association between the heat vulnerability index and risk of heat-related deaths in both urban and non-urban settings (El-Zein and Tonmoy, 2015; Loughnan et al., 2012; Wang et al., 2023; Zhang et al., 2018).

Understanding heatwave vulnerability index and the related mortality relationship in the context of a larger geographical scale is important because it accounts for socioeconomic disparities across both urban and non-urban areas to help design national heatwave vulnerability interventions. In this study, we collated all-cause mortality data consisting of 2189 Statistical Area Level 2 (SA2s)- spatial units with generally 3000–25,000 people across Australia from 2001 to 2019 to assess if heatwave vulnerability is associated with risk of heatwave-related deaths.

Because heatwaves are more detrimental to human health than other heat-related extremes, heatwave vulnerability index (HVI) is an important metric used to locate population's vulnerability to heatwaves (Manware et al., 2022; Reid et al., 2009; Wang et al., 2023). The overarching goal of this study is to validate heatwave vulnerability index (HVI) using heatwave-related deaths across Australia. The three specific objectives of this study were to: (1) quantify heatwave-related deaths; (2) examined the association between HVI, and risk of heatwave-related deaths; and (3) explore the association between HVI and heatwave-related deaths for different heatwave severity categories (i.e., low-intensity, severe, and extreme heatwave).

The contributions of this study are as follows. First, in terms of new experimental data, we included nearly two decades (2001–2019) of all-cause mortality data for each of the 2189 spatial units. The large sample size and the longitudinal death cases lacking in previous studies (focused on a few areas, used aggregated health data) enabled us to conduct a comprehensive analysis to maximize the validity of our findings. Second, different from previously published studies, the range of heatwave types (low-intensity heatwave, severe heatwave, and extreme heatwave), provided us a unique opportunity to systematically examine the predictive ability of HVI on heatwave-related deaths under varying heatwave severities. Third, we employed observed temperature data (2001–2019) to define heatwave using the excess heat factor (EHF) metric and conducted an exposure assessment for each of the 2189 individual spatial units. EHF is the most impactful and robust metric for characterizing heatwaves to achieve accurate exposure estimates. EHF accounts for inherent humidity, acclimatization, and deviation from historical (past 20 years) temperature thresholds (95th percentile mean temperature), and recent 30-day mean temperature (Kanti et al., 2022). In addition, our time-series study design can yield accurate estimates of an individual spatial unit heatwave-related deaths as the stable mortality rates used were smoothed by borrowing the strength of mortality rates from surrounding spatial units. Finally, besides the new methodological approach used in examining the risk of heatwave-related deaths, this study also advances our empirical knowledge of heatwave management in the Indo-Pacific region through geospatial science, public health, and climate policy research.

2. Materials and methods

2.1. Study area

The study was conducted at a Statistical Area Level 2 (SA2) unit across Australia and its capital cities (Melbourne, Sydney, Adelaide, Brisbane, Hobart, Perth, Darwin). SA2 is a medium size spatial unit in Australia with an estimated average population size of 10,000 people (Chaston et al., 2022). There are 2473 SA2s in Australia distributed across urban, rural, and remote areas (Australian Bureau of Statistics, 2021). The average area (km^2), and population size of SA2s in each state and territory across Australia is presented in Fig. S1.

2.2. Mortality

We obtained a total of 2,794,053 all-cause mortality data covering 2459 populated SA2s across Australia from the Australian Bureau of Statistics between 2001 and 2019. We focused on deaths that occurred in December–February, the hottest summer months in Australia. Data cleaning involved the removal of non-populated SA2s such as migratory, offshore – shipping, SA2s without geocodes, special purpose, and those outside Australia. The total SA2s that were finally included in the analysis were 2189 representing a total of 588,594 deaths (2001–2019).

2.3. Heatwave

We obtained nationwide SA2-level daily surface minimum and maximum temperature data (2001–2019) from the Australian Bureau of Meteorology (BOM, 2010). We calculated heatwaves using the areal mean of the surface temperatures at a spatial resolution of $0.05^\circ \times 0.05^\circ$ (approximately 5 km) for all the summer months (December–February) for each SA2 region across Australia (Jones et al., 2009). Excess Heat Factor (EHF) heatwave exposure metric was used for the heatwaves calculation (Nairn and Fawcett, 2015).

In each SA2, we calculated EHF by comparing the three-day mean daily temperature ($DMT_{3\text{-days}}$) with the 95th percentile mean temperature (DMT_{95th}) for all days spanning from 2001 to 2019 (long-term period), and with the preceding 30-day mean temperature ($DMT_{30\text{-days}}$), the short-term period. EHF ($^\circ C^2$) was obtained by combining the long-term temperature anomaly: excess heat index significance (EHI_{sig}) with the short-term temperature anomaly: excess heat index acclimatization (EHI_{accl}). A heatwave day was defined as occurring for three days in a row when EHF was greater than 1 for each SA2 (Nairn et al., 2022).

Finally, we classified EHF into three heatwave severity categories. This is done by calculating the ratio of EHF to the 85th percentile mean daily temperature levels from 2001 to 2019 (EHF/EHF_{85th}). We obtained the three heatwave severity categories as low-intensity heatwave (0 to 1), severe heatwave (1 to $<$3), and extreme heatwave ($\geq$ 3) when EHF/EHF_{85th} was 0–1, 1- $<$3, and $\geq$ 3, respectively (Nairn and Fawcett, 2015). Because our mortality data was seasonal (December–February), we aggregated the number of heatwave days for all three months across 2001–2019 and used it as exposure of interest for the heatwave-related mortality risk calculation.

2.4. Heatwave vulnerability index

2.4.1. Spatial scales, data sources, and variable selection

We used both national ($N = 2189$ SA2s) and capital cities ($N = 1152$ SA2s) scale HVI data estimated from 2021 national census data and heatwave data (2001–2019) for this study. The HVI was developed from a total of 14 heat vulnerability indicators composed of EHF (i.e., occurrence of heatwave days), demographic (i.e., older people ≥65 years, English speaking ability, low education, living alone, non-Australians, Indigenous), socioeconomic (i.e., low income, unemployment, home ownership), land cover (i.e., impervious surfaces), and health (i.e., diabetes, asthma, healthcare professionals) variables. All the data were obtained from the Australian Bureau of Statistics, Bureau of Meteorology, and Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

2.4.2. Calculation of heatwave vulnerability index

We created HVI following the Intergovernmental Panel on Climate Change (IPCC)'s vulnerability framework as a function of exposure, sensitivity, and adaptive capacity based on the characteristics of the selected indicators shown in Table S1 (IPCC, 2014). This concept of vulnerability has been widely used to develop HVI in Asia (Adnan et al., 2024; Tran et al., 2020), Europe/United Kingdom (Buzási, 2022; Wolf and McGregor, 2013), and North America (Bradford et al., 2015; Conlon et al., 2020; Ho et al., 2018; Manware et al., 2022). Following Reid et al. (2009), our indicators were selected based on evidence from epidemiological studies showing their association with heat-related deaths and morbidities (Table S2).

We used principal component analysis (PCA) to calculate the HVI. This technique creates uncorrelated and independent factors that contribute to vulnerability (Reid et al., 2009). To calculate HVI for each SA2, we conducted spearman's correlation matrix (Fig. S2), and then applied PCA to the 14 indicators to generate four factors. The detailed description of the four HVI factors are shown in Table 1. We selected factors whose eigenvalues >1, and normalized their factor scores (i.e., mean equal zero, and standard deviation equal 1).

Following Bradford et al. (2015), we characterized factors for indicators whose cut-off coefficient values were ≥ 0. 6.We further classified the factors from scale of 1 (least vulnerability) to 6 (highest vulnerability) based on their standard deviation from the mean. The HVI score (continuous variables) was obtained by the sum of the four factors. Finally, the HVI score was normalized, and re-classified again to scale of 1–6 (categorical variables) for easy interpretation (Reid et al., 2009). All the analysis was performed using the '*PROC FACTOR*' command of SAS software (version 9.4).

Table 1
Description of HVI factors. The numbers in the bracket are cut-off correlation coefficient values of ≥0.6 indicating significant loadings on each HVI factor.

HVI Factors	National scale ($N = 2189$ SA2s)	Capital city scale ($N = 1152$ SA2s)
Factor 1	Percentage of populations with <12th-year education ($r = 0.68$), low income (r = 0.89), without healthcare professionals ($r = 0.69$), and diabetes ($r = 0.89$)	Percentage of populations with <12th-year education (r = 0.69), low income ($r = 0.92$), without healthcare professionals ($r = 0.78$), and diabetes ($r = 0.91$)
Factor 2	Percentage of populations who are unemployed ($r = 0.73$), and without homeownership (r = 0.92)	Percentage of populations whose English language not well ($r = 0.81$), are not Australian ($r = 0.65$)
Factor 3	Percentage of populations whose English language is not well ($r = 0.85$), and are not Australians ($r = 0.64$)	Percentage of populations who are unemployed (r = 0.64), and without homeownership($r = 0.93$)
Factor 4	Percentage of populations who are Indigenous ($r = 0.72$), and have heatwave days ($r = 0.76$)	Percentage of populations live alone (r = 0.91) and have impervious surface ($r = 0.61$)

Note: Asthma and elderly (> 65 years old) variables/indicators were included in the analysis but could not load onto any of the factors with coefficient values were ≥ 0.6. Heatwave days were determined from EHF, Indigenous composed of Aboriginal, Torres Strait Islander, Aboriginal, and Torres Strait Islander. The impervious surface was calculated from non-vegetated areas of each SA2. Income was based on households whose equivalized annual income was below national levels.

2.5. Statistical analysis

Three-stage analyses were conducted to determine the association between HVI and heatwave-related deaths across the SA2s in Australia. First, we estimated the mortality rates of each SA2 using a spatial empirical Bayes smoothing approach. Second, we applied a quasi-Poisson regression model to estimate the association between suburb-specific heatwaves and all-cause mortality rates (per 100,000 individuals). Finally, we used simple regression analysis to examine the relationship between HVI and risk of heatwave-related deaths.

2.5.1. Stage-1: Mortality rates

We calculated SA2 level, population-adjusted seasonal (December–February) all-cause mortality rates for the years 2001–2019 across Australia and the greater cities. Mortality rates for smaller areas are prone to instability because of potential large changes that occur due to small changes in the absolute number of deaths (Khatana et al., 2022). These instabilities were corrected through the spatial empirical Bayes smoothing approach (Anselin et al., 2006a). This technique combines the raw SA2-specific mortality rate with the overall national/capital cities scale mortality rates (i.e., reference rates), and then estimates a weighted mortality rate from the two, with direct proportionality to their populations. This enables substantial adjustments to occur among smaller populated SA2s compared to the larger SA2s.

Bayesian smoothing rates are calculated by first identifying the Poisson distribution of the observed counts of deaths, and a prior Gamma distribution (calculated from the actual data and is considered as a reference mortality rate) which assumes a negative binomial distribution.

To determine Bayesian smoothing rates for SA2 *i,* the following equations were used.

$$\text{Bayes Smooth Rate}_i = \omega_i + \text{Raw Rate}_i + (1 - \omega_i) \times \text{Reference Rate}_i$$

The weight ω is estimated according to:

$$\omega_i \frac{\sigma^2}{(\sigma^2 + \mu/\text{Pop}_i)}$$

Where σ^2, μ, and Pop_irepresent variance, prior distribution mean, and population for SA2 *i*, respectively.

μ and σ^2 are also estimated according to:

$$\mu = \frac{\sum_{j=n}^{i=n} \text{Observed Deaths}_i}{\sum_{j=n}^{i=n} \text{Pop}_i}$$

$$\sigma^2 = \frac{\sum_{j=n}^{i=n} \text{Pop}_i\ (\text{Raw Rate}_i - \mu)^2}{\sum_{j=n}^{i=n} \text{Pop}_i} - \frac{\mu}{\sum_{j=n}^{i=n} \text{Pop}_i \Big/ N}$$

N indicates the total number of suburbs within the reference sample.

All SA2-level mortality rates were calculated separately for the entire Australia, and the greater cities using Geoda Software, version 2.11

(Anselin et al., 2006b).

2.5.2. Stage 2: Heatwave-mortality relationship

We applied longitudinal study design on population-adjusted spatial empirical Bayes smoothed seasonal (December to February) mortality rates, and the number of heatwave days for each of the 2189 SA2s across Australia from 2001 to 2019. We applied Generalized Linear Models (glm) with the quasi-Poisson distribution family to estimate the SA2-specific effect of heatwaves on mortality risks. This association was assumed to be a linear relationship by applying the log-link functions for all-cause mortality rates to ensure overdispersion (Curriero et al., 2002).

The model fairly accounted for relative humidity as the heatwave metric (i.e., EHF) used inherently computed for interaction between SA2-specific relative humidity and minimum temperature levels (Nairn and Fawcett, 2015; Oliveira et al., 2022; Wondmagegn et al., 2021). Since the mortality and heatwave data were seasonal data, we could not adjust for delay effects, or long-term trends but rather included variations in years to account for secular time trends (Khatana et al., 2022). In addition, this methodology is consistent with previous research that examined heat-mortality association from summer temperature and mortality data (Ballester et al., 2023).

We further computed heatwave-related deaths according to different heatwave types (low-intensity heatwave, severe heatwave, and extreme heatwave) to better understand how different heatwave intensities influence heatwave-mortality relationships (Franklin et al., 2023). The full description of the dose-response model used in this study is indicated by the following equation:

$$Y_t \sim Poisson\ (E_{imt})$$

$$Log(E_{imt}) = \alpha + \beta(hwd_{imt}) + nYear_{it}$$

E_{imt} is population adjusted, empirical Bayes smoothed deaths (per 100,000 individuals) in SA2 i for season m (December–February) in year t (2001–2019), hwd_{imt} is the number of heatwave days in season m and time t in SA2 i, ${}_nYear_{it}$ is years t accounting for variations in secular time trends in SA2 i. This analysis was conducted at two spatial scales: (1) nationwide, and (2) the capital cities, the association were reported as percentage (%) of heatwave-related deaths.

All the analysis was conducted using the glm package of STATA software (version 18) (College Station, TX, United States) (StataCorp, 2023). The spatial mapping of the AF was performed with ArcGIS Pro (version 3.1.0).

2.5.3. Stage 3: Validation of HVI with heatwave-related deaths

First, we applied Pearson's correlation analysis to explore the strength of relationship between HVI and heatwave-related deaths. This analysis was conducted for the whole of Australia, and the capital cities. Second, we applied linear regression analysis to determine if HVI (independent variable) is a predictor of heatwave-related deaths (as dependent variable). For each spatial scale, we stratified the analysis according to heatwave severities. We examined the association between HVI, and the related deaths derived from the three heatwave severities: (i) severe, (ii) extreme/severe, and (iii) low-intensity heatwave. The potential multicollinearity among the dependent and the independent variables were tested. The variance inflation factor (VIF) of 1, indicates no correlation among the variables (Daoud, 2017). The association was reported as 95 % confidence intervals (CI), taking the values of $p < 0.05$ statistically significant. The analysis was performed using STATA software (version 18) (College Station, TX, United States).

2.6. Sensitivity analysis

We tested the robustness of our findings by conducting a sensitivity analysis across the SA2 spatial units at both national and capital cities level. We developed a new HVI but reduced the number of indicators from 14 to 10 (Table S1). These new 10 indicators include the number of heatwave days, % elderly population (>65 years), % population whose spoken English proficiency is not well, % lone person household, % less than 12-year education, % non-Austrians, % Indigenous population, % household with low-income, % diabetes, and % asthma, these indicators were selected because they are widely used in HVI studies (Li et al., 2023; Manware et al., 2022; Reid et al., 2009). Therefore, the indicators that were excluded from the analysis are % impervious surface, % without home ownership, % without healthcare professionals, and % unemployment. The description of the 10 selected indicators is shown in Table S3. We applied the same study design, and PCA technique previously used by Reid et al. (2009) to develop the HVI by summing up the individual HVI factors, shown in Table S4.

Finally, the relationship between HVI and heatwave-related deaths was conducted using both simple Pearson's correlation, and linear regression analysis. The results were reported as a 95th confidence interval ($p < 0.05$). All the statistical analysis was performed using STATA software (version 18) (College Station, TX, United States).

2.7. Ethical approval

The study was exempted from ethical review (Project# 2022/HE001428) according to the University of Queensland's Human Research Ethics Committees (HRECs) guidelines. The review was waived because this retrospective study used SA2-level deidentified all-cause mortality data.

3. Results

3.1. Descriptive statistics of heatwaves and mortality

Table 2 presents the summary statistics of SA2-level heatwave days, all-cause mortality, and HVI across Australia ($N = 2189$ SA2s), and the

Table 2
Summary statistics of SA2-level seasonal (December–February) count of deaths, all-cause mortality rates (per 100,0000), number of heatwave days and the three heatwave intensity categories (extreme, severe, and low-intensity heatwave days), and HVI at Australia-wide ($N = 2189$ SA2s), and the capital cities (N = 1152 SA2s) between 2001 and 2019.

Category	Mean	SD	25th P	75th P	95th P
(A) Australia (N = 2189 SA2s)					
Population	9292.51	5397.58	4943	12,994.5	19,532
Death Counts	14.15	11.60	6	20	37
Mortality Rate (per 100,000)	148.60	176.42	95.9	188	276.1
Heatwave Days	25.64	14.09	15	34	51
Extreme	0.44	1.19	0	0	3
Severe	3.67	3.74	0	5	11
Low-intensity	21.53	11.81	13	29	43
HVI values (continuous)	13.91	1.77	13	15	17
HVI scores 1–6 (%)	1 (0.59)	2 (18.55)	5 (12.06)	6(3.29)	
(B) †Capital cities (N = 1152 SA2s)					
Population	10,844.21	5586.42	6523	14,941.75	20,657
Death Counts	14.81	11.67	6	21	36
Mortality Rate (per 100,000)	133.94	226.36	85.3	161.9	248.365
Heatwave Days	23.74	13.24	14	31	50
Extreme	0.41	1.11	0	0	3
Severe	3.39	3.48	0	5	9
Low-intensity	19.94	11.19	12	27	41
HVI values (continuous)	14.01	2.02	13	15	17
HVI scores 1–6 (%)	1 (0.17)	2(9.98)	5(8.77)	6(2.52)	

Note: SD: Standard deviation, Max: Maximum, P: Percentile, †Capital cities (Sydney, Melbourne, Brisbane, Adelaide, Perth, Hobart, Darwin). HVI scores 1–6 indicate the lowest to highest heat vulnerability.

capital cities ($N = 1152$ SA2s). The average population size from the capital cities over the period 2001–2019 was 10,844 people, which was higher than the national estimates of 9292 people (Table 2).

About 12.06 % and 3.29 % of SA2s across Australia achieved higher HVI scores ranging from 5 to 6, than the capital cities of 8.77 % and 2.52 %, respectively because they contain many remote/regional SA2s which are mostly socio-economically disadvantaged (Table 2). However, the mean, and percentiles (25th, 75th, and 95th) HVI scores did not change much both at the national scale and at the capital cities (Table 2). The spatial pattern of HVI showed that HVI increased among the larger SA2s found within the northern and southwestern parts of Australia (Fig. 1). Similarly, there is evidence of increasing clusters of high heat vulnerability across the northern Australia according to Fig. 1.

The average counts of seasonal deaths from 2001 to 2019 across Australia was 14.15, depending on the population size of the SA2s. This was similar to the greater cities (mean = 14.81 deaths). To account for variations in population size, we observed a higher average mortality rate across Australia (149 deaths/100,000 people) than the greater cities (134 deaths/100,000 people) (Table 2). We observed that the average number of seasonal heatwave days (2001 to 2019) was slightly high across Australia (25.64 heatwave days) compared to its greater cities (23.74 heatwave days) including the extreme, severe, and low-intensity heatwave days (Table 2).

Fig. 2 shows the temporal trend in average heatwave days and seasonal mortality rates across the SA2s in Australia over the 20-year period 2001–2019. Although, the visual relationship between heatwave days and mortality was non-linear during the first decade but became linear during the last decade (2012–2019), particularly during the last 3 years (2016–2019). As shown in Fig. 2, during the period 2001–2019, Australians experienced higher fluctuations in the average number of seasonal heatwave days during the first decade (2001−2011) and then increased steadily during the second decade (2012–2019). Nationally, the highest seasonal mortality rate occurred in 2006 (156.38 deaths/100,000 people), slightly reduced to 143.47/100,000 in 2010, and slowly increased again from 2011 to 2019 (Fig. 2).

3.2. Spatial variations in mortality rates and heatwave days

To account for spatial variations in all-cause mortality and heatwave days, Fig. 3A shows the distribution of seasonal mortality rates (per 100,000 people) across Australian SA2s during 2001–2019. We found that the lowest seasonal mortality rates indicated by the first quartile (103 deaths /100,000 people) occurred among SA2s in Western Australia, particularly in the cities of Port Hedland, Exmouth, and Esperance. The SA2s within Victoria and New South Wales including their capital cities showed the highest mortality rates: the fourth quartile deaths ranged from 185 to 18,609 /100,000 people. Whereas the third quartile deaths (142–185/100,000 people) were common in SA2s within Queensland (e.g., Cairns, Townsville, and Toowoomba), and the Northern Territory except in Darwin which lies within the first quartile.

With regards to heatwave levels (Fig. 3B), we observed the highest heatwave days across 11 SA2s located in Western Australia, South

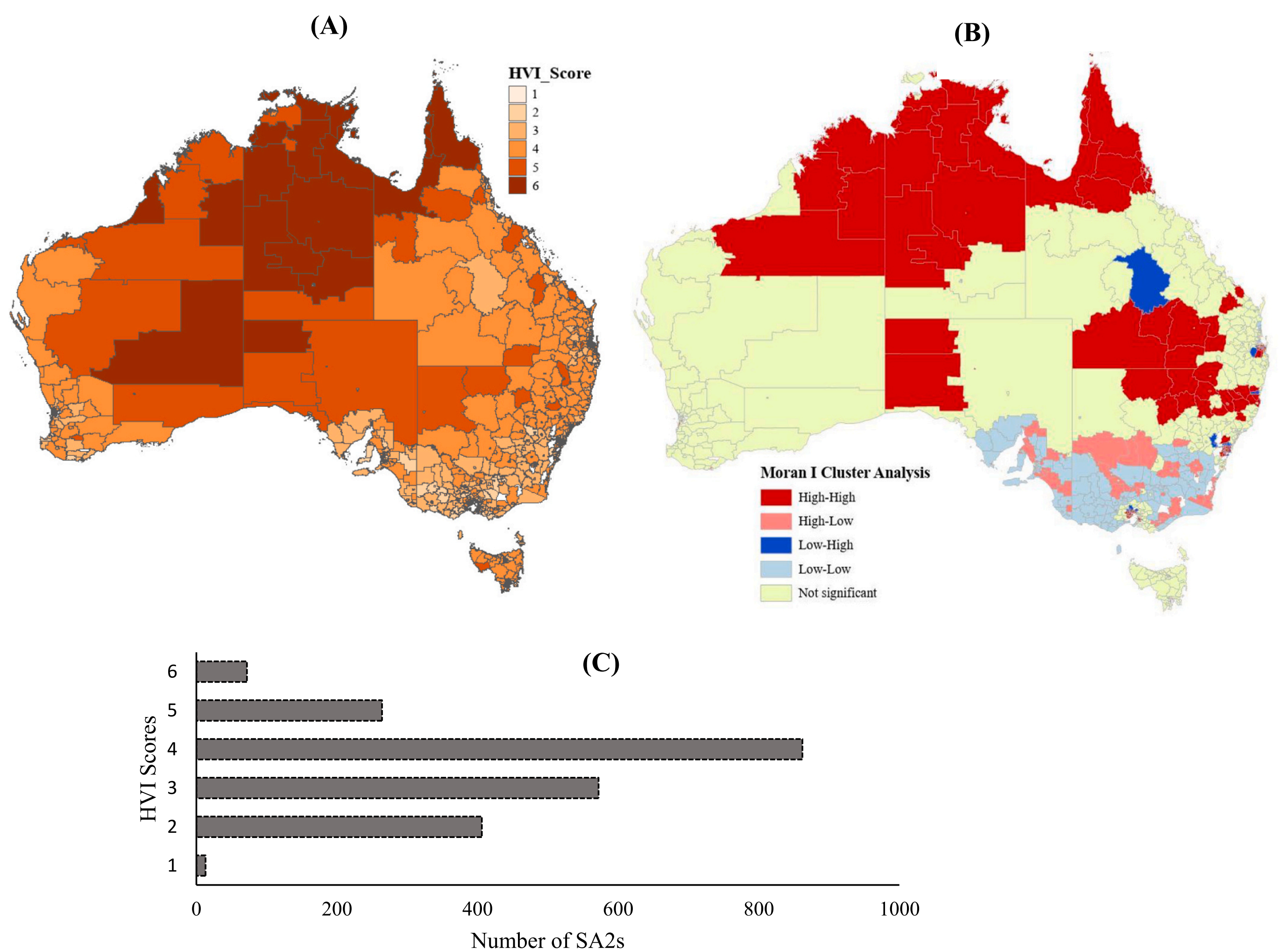

Fig. 1. A map showing (A) distribution of HVI scores, (B) Local Moran I's spatial clusters of HVI, and (C) frequencies of HVI scores across Australia ($N = 2189$ SA2s during 2001–2019. Note: the grey color in (A) indicates SA2s without data.

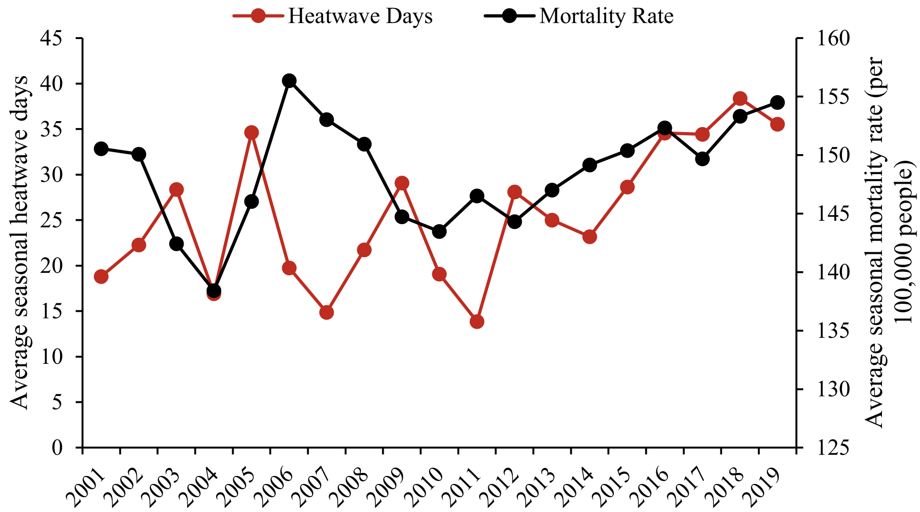

Fig. 2. The average seasonal (December–February) suburb level (N = 2189 SA2s) all-cause mortality rates (per 100,000 people) from 2001 to 2019 indicated by black color (the mortality rates were smooth with spatial empirical Bayes Smoothing to account for SA2-level mortality rates instability), and average seasonal heatwave days ($N = 2198$ SA2s) shown by red color in Australia (Heatwave is defined in each SA2 as a three-day mean daily temperature in a row when EHF > 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Australia (e.g., north-southeast), Queensland (e.g., north-southwestern part) including Cairns. In the greater cities, which constitute nearly 67 % of the Australian population, about 1473 SA2s experienced 22–36 heatwave days between 2001 and 2019 during the summer season (December–February). Overall, Australia's average low-intensity heatwave days (22 days) was far higher than severe heatwave days (Fig. 3C).

3.3. Heatwave-related deaths

The spatial distribution of % increase in heatwave-related deaths across 2198 SA2s in Australia is shown in Fig. 4. We observed high heterogeneity of heatwave-related deaths across the SA2s, these range from −19.48 % deaths from the first quartile to 26.58 % deaths from the fourth quartile distribution. A higher risk of deaths (0.42 %–26.58 %) was found in the far north and southern part of Western Australia, with hotspots within the capital cities of Victoria, Queensland, and Tasmania. SA2s found within northeastern and southeastern Australia had % increase in heatwave-related deaths ranging from 0.05 % to 0.42 % (Fig. 4). We found that 547 SA2s were highly protective to heatwave-related deaths, ranging from −19.48 % to −0.29 %, particularly in central South Australia, southwestern Western Australia, and northeastern Queensland.

Fig. S3 displays the distribution of heatwave-related deaths across Australia according to different heatwave severities: extreme, extreme/severe, and low-intensity heatwaves. Most of the heatwave severities show consistent patterns of death distribution across Australia. There was a higher risk of deaths found mostly in central Queensland, southeastern and southwestern parts of Perth, New South Wales, and Victoria, and some hotspots in Tasmania common to all heatwave intensity levels (Fig. S3).

We found that third (0.21 %–1.60 %) and fourth (1.6 %–28.27 %) quartile distribution of severe heatwave-related deaths (Fig. S3, A) were similar to extreme/severe heatwave-related deaths of 0.25 %–1.52 % and 1.52 %–28.46 %, respectively (Fig. S3, B). The risk of heatwave attributed deaths due to low-intensity heatwaves for both the third (0.03 %–0.48 %) and fourth (0.48 %–17.16 %) quartile distribution was relatively lower when compared to the extreme and severe heatwave-related deaths (Fig. S3, C).

3.4. HVI – % of heatwave-related deaths relationship

The performance of HVI through the relationship with % of heatwave-related deaths across Australia is presented in Table 3. Nationally, there was no correlation between HVI and heatwave-related deaths (ρ = −0.02, *p*-value = 0.28) occurring during the period 2001–2019. Although high heatwave intensity periods normally excite risk of deaths, we found that there was no correlation between HVI and attributable deaths caused by severe (ρ = −0.00, p-value = 0.94) and extreme/severe (ρ = −0.00, p-value = 0.97) intensity heatwaves thresholds (Table 3).

For the individual vulnerability factors, results suggest that factor 1 (less than 12-year education/low income/non-health professionals/diabetes prevalence) which is often characterized by a high risk of death did not show correlation (ρ = −0.05, p-value = 0.03) with heatwave-related deaths in Australia. Similar findings were observed in factor 2 (unemployed, without homeownership), factor 3 (English language not well/ Not Australian), and factor 4 (Excess heat factor/ indigenous) for all the deaths related to the different heatwave severities, presented in Table 3.

At the national level, the association between HVI/factors as predictor variables and % of heatwave-related deaths as response variable is shown in Table 4. We found that HVI was not associated (p>0.05) with risk of deaths attributed to both heatwave and its intensities. Regressing the HVI with heatwave-related deaths yielded an R^2 value of 0.00 when the analysis was performed for the overall heatwave, and low-intensity, severe, and extreme/severe heatwave-related deaths.

Among the HVI factors, we observed that only factor 2 (unemployed, without homeownership) was positively associated ($p = 0.02$) with % of severe-related deaths (Table 4). Factor 4 (excess heat factor/Indigenous) showed the strongest association ($p = 0.00$) with heatwave-related deaths from both the overall heatwave and its intensities. However, the magnitude ($R^2 = 0.01$) of the association was small and did not vary with different heatwave-related deaths (Table 4).

We examined the relationship between the capital cities level HVI and increased in % of heatwave-related deaths. Table 5 presents the relationship between HVI including its factors, % heatwave-related deaths, and the heatwave severities at the capital city scale. We found a weaker statistically significant correlation (ρ = 0.11, *p*-value = 0.00) between city scale HVI and heatwave-related deaths. With regards to the HVI factors, we found that there was relatively higher correlation between factor 1 (ρ = 0.19, *p*-value = 0.00) and % of heatwave-related deaths than the remaining three vulnerability factors (i.e., factor 2, factor 3, and factor 4).

The magnitude of the effect of HVI on deaths associated with the

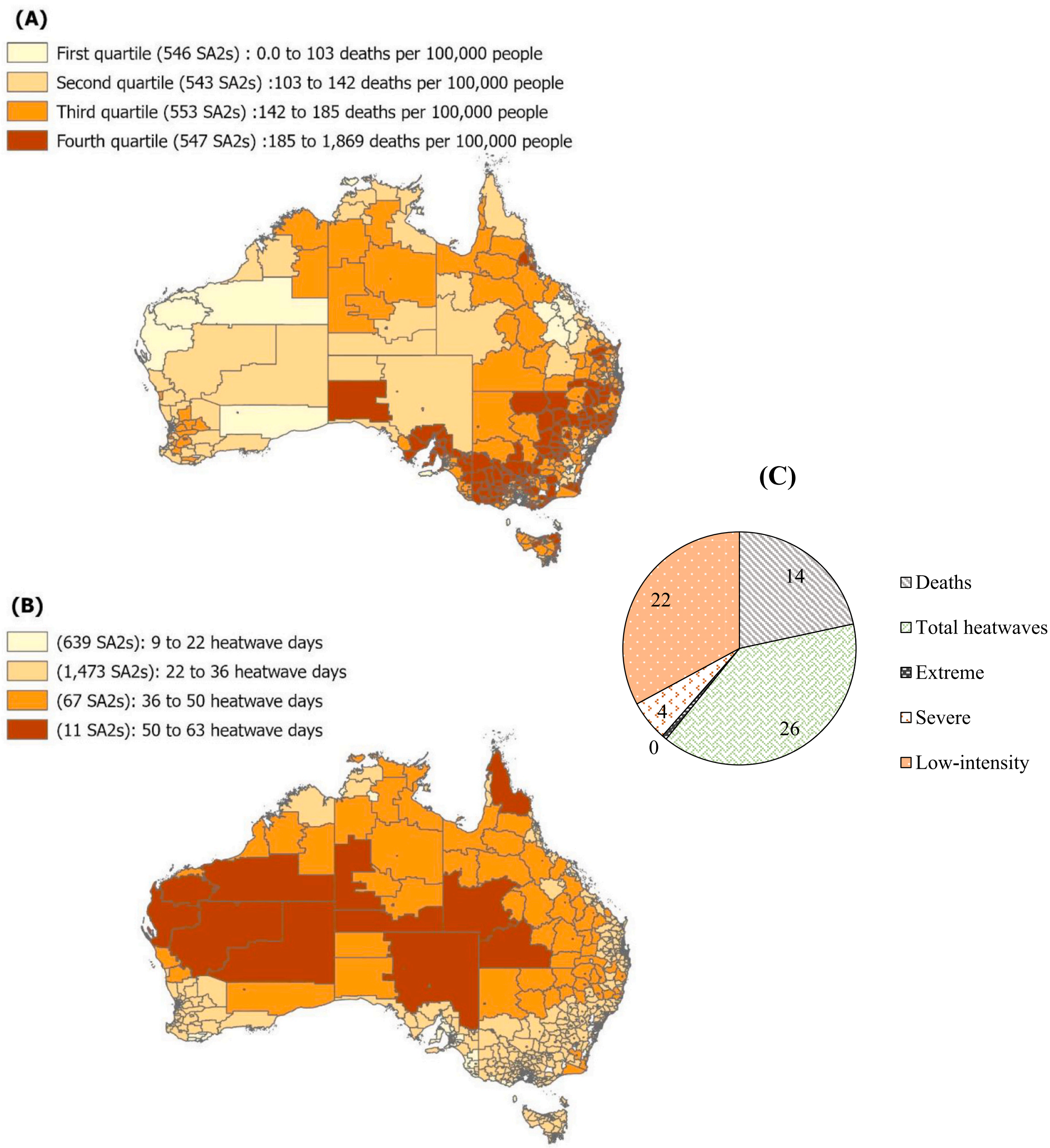

Fig. 3. Australian SA2 ($N = 2198$ SA2s) level spatial map showing mean seasonal all-cause mortality rates and average number of seasonal (December–February) heatwave days from 2001 to 2019. (A) Quartiles of SA2s by mean seasonal (December–February) population-adjusted all-cause mortality rates derived from spatial empirical Bayes smoothing approach from 2001 to 2019, (B) SA2 level mean seasonal (December–February) heatwave days, and (C) average deaths, heatwaves days, and the three heatwave severity days (extreme, severe, and low-intensity heatwave days) from 2001 to 2019.

heatwave intensities were also evaluated at capital city levels (Table 5). Although a weaker correlation was observed, the relationship between HVI and low-intensity heatwave-related deaths ($\rho = 0.11$, p-value $= 0.00$) was better than severe ($\rho = 0.06$, p-value $= 0.00$), and extreme/ severe ($\rho = 0.07$, p-value $= 0.00$) heatwave-associated deaths.

With regards to the strength of relationship with heatwave vulnerability factors, both factor 1 ($\rho = 0.18$, p-value $= 0.00$) and factor 2 ($\rho = 0.17$, p-value $= 0.00$) showed relatively higher statistically significant correlation with low-intensity heatwave-related deaths than the remaining heatwave severities.

At the capital cities scale, we found statistically a significant association between overall HVI score, and risk of heatwave-related deaths (Table 6). Thus, a unit increase in overall HVI increases the % of heatwave-related deaths by 0.18 (β: 0.18, 95 % CI: 0.08–0.27). This was higher for severe intensity heatwave deaths (β: 0.39, 95 % CI: 0.05–0.74) compared to low-intensity heatwave deaths (β: 0.21, 95 % CI: 0.09–0.32).

For HVI factors analysis, only factor 4 (living alone/impervious surface) did not show association with risk of heatwave-associated deaths including deaths from the three heatwave intensities (Table 6). Generally, we found stronger the magnitude ($R^2 = 0.02$–0.04) of the association in factor 1(less than 12-year education/low income/non-health professionals/ diabetes prevalence) with all the heatwave-related deaths compared to the other HVI factors (Table 6). Overall, the unit increase in HVI factors, particularly factor 1 and factor 2 (English language not well/non-Australians), and % increased risk of death

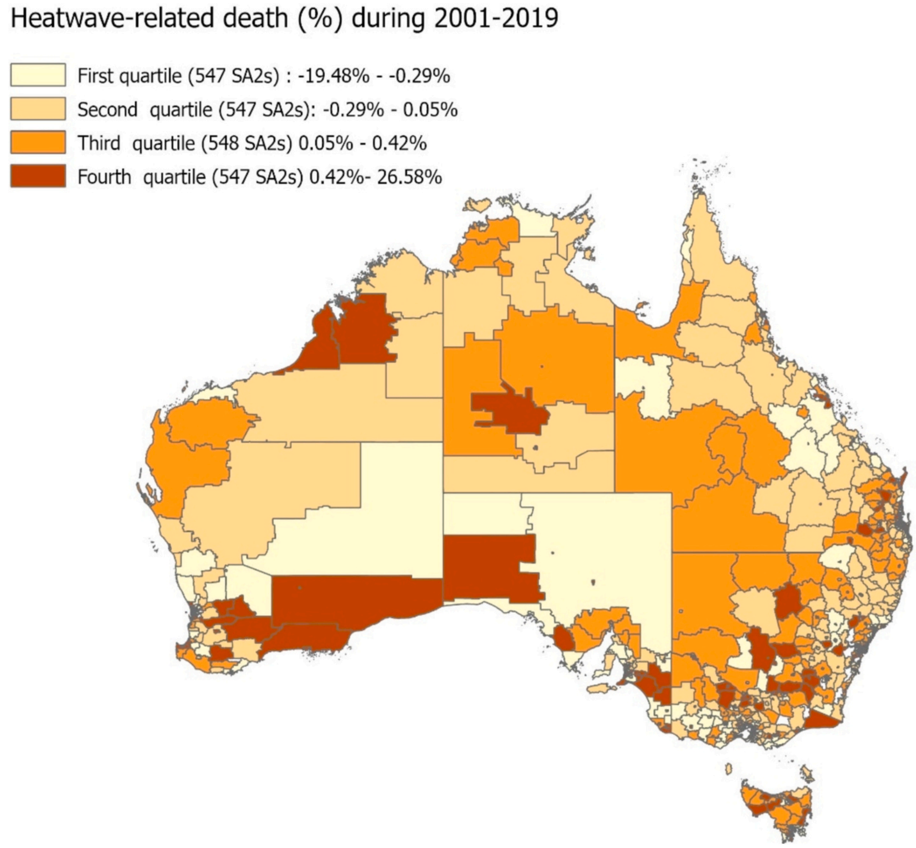

Fig. 4. Quartiles distribution of SA2 level (N = 2, 189 SA2s) heatwave-related deaths (%) across Australia.

Table 3
Australia-wide ($N = 2189$ SA2s) Spearman's correlation (ρ) analysis at 95 % confidence interval (CI) between heatwave-health vulnerability index (HVI) scores, the individual HVI factors, and % of heatwave-related deaths categorize according to overall heatwave, severe, extreme/severe, and low-intensity heatwave categories.

Variable (Predictors)	N	Heatwave-related deaths (%)		Severe intensity heatwave-related deaths (%)		Extreme /severe intensity heatwave-related deaths (%)		Low-intensity heatwave-related deaths (%)	
		ρ	*P-value	ρ	*P-value	ρ	*P-value	ρ	*P-value
HVI	2189	−0.02	0.28	−0.00	0.94	−0.00	0.97	−0.01	0.65
Factor 1	2189	−0.05	0.03	0.05	0.01	0.04	0.05	0.00	0.97
Factor 2	2189	0.03	0.19	−0.05	0.01	−0.03	0.17	−0.01	0.50
Factor 3	2189	0.04	0.03	0.04	0.03	0.05	0.01	0.07	0.00
Factor 4	2189	−0.09	0.00	−0.07	0.00	−0.09	0.00	−0.09	0.00

Note: Factor 1: Less than 12-year education/low income/non-health professionals/diabetes prevalence, Factor 2: unemployed, without homeownership, Factor 3: English language not well/ Not Australian, Factor 4: Excess heat factor /indigenous.

was higher during severe heatwave days than low-intensity heatwave days.

3.5. *Sensitivity analysis*

Our sensitivity analysis partly agrees with the main findings, the results suggest a lack of association between HVI and an increase in % of heatwave-related deaths across Australia (Tables S5-S6). Also, with regards to the capital city scale HVI-deaths relationship, we did not observe any association in this sensitivity analysis in contrast to the main results where a weaker association was found. However, a statistically significant association was observed for factor 1 ($\rho = 0.18$, p-value $= 0.00$) and heatwave-related deaths at the city scale. The same factor 1 experienced a stronger association with low-intensity heatwave-related deaths ($\rho = 0.17$, p-value $= 0.00$) than the remaining heatwave types.

Regarding the regression analysis (Table S6), the sensitivity analysis suggests no statistical significance ($p > 0.05$) association between the HVI scores and risk of heatwave-related deaths at both Australian-wide and the capital cities scale analysis. However, only factor 1 (less than 12th education /low income /diabetes prevalence), and factor 3 (Indigenous/ excess heat factor) showed positive association ($p < 0.05$) with risk of death in Australia. For the capital cities, factor 1 (less than 12th education /low income /diabetes prevalence),and factor 3 (Indigenous) showed stronger association ($p < 0.05$) with heatwave-associated deaths.

4. Discussion

To our current knowledge, this is the largest SA2-level study to examine the association between heatwave vulnerability index (HVI) and heatwave-related deaths (2001 to 2019) in Australia. We applied generalized linear models with a quasi-Poisson distribution family to estimate SA2-specific % of heatwave-related deaths across from 2, 189 SA2s across Australia, the capital cities, and then further examined their association with HVI.

Table 4
Australia-wide (N = 2, 189 SA2s) linear regression analysis at 95 % confidence interval (CI) for association between one-unit increase in heatwave-health vulnerability index (HVI), the individual HVI factors, and % of heatwave-related deaths from overall heatwave, severe, extreme/severe, and low-intensity heatwave severities.

Variable (Predictors)	Heatwave-related deaths (%)			Severe intensity heatwave-related deaths (%)			Extreme/severe intensity heatwave-related deaths (%)			Low-intensity heatwave-related deaths (%)		
	β (95 % CI)	P-value	R^2	β (95 % CI)	*P*-value	R^2	β (95 % CI)	P-value	R^2	β (95 % CI)	P-value	R^2
HVI	−0.06 (−0.17–0.05)	0.28	0.00	−0.01 (−0.19–0.18)	0.95	0.00	−0.00 (−0.17–0.16)	0.98	0.00	−0.02 (−0.09–0.06)	0.65	0.00
Factor 1	−0.13 (−0.24- -0.01)	0.03	0.00	0.25 (0.06–0.44)	0.01	0.00	0.16 (−0.00- -0.33)	0.05	0.00	0.00 (−0.08–0.08)	0.97	0.00
Factor 2	0.08 (−0.04–0.19)	0.19	0.00	−0.23 (−0.42- -0.04)	0.02	0.00	−0.12 (−0.28–0.05)	0.17	0.00	−0.03 (−0.11–0.05)	0.50	0.00
Factor 3	0.13 (0.01–0.25)	0.03	0.00	0.22 (0.02–0.42)	0.03	0.00	0.22 (0.04–0.39)	0.01	0.00	0.16 (0.07–0.24)	0.00	0.01
Factor 4	−0.29 (−0.43- -0.15)	0.00	0.01	−0.43 (−0.66- -0.19)	0.00	0.01	−0.44 (−0.65- -0.24)	0.00	0.01	−0.23 (−0.33- -0.12)	0.00	0.01

Note: Factor 1: Less than 12-year education/low income/non-health professionals/diabetes prevalence, Factor 2: unemployed, without homeownership, Factor 3: English language not well/ Not Australian, Factor 4: Excess heat factor/Indigenous. Note: variance inflation factor (VIF) of 1 suggests no multicollinearity among the dependent and independent variables.

Table 5
Capital cities scale (*N* = 1152 SA2s) Spearman's correlation (ρ) analysis at 95 % confidence interval (CI) between heatwave-health vulnerability index (HVI) scores, the individual HVI factors, and % of heatwave-related deaths based on overall heatwave, severe, extreme/severe, and low-intensity heatwave categories.

Variable (Predictors)	N	Heatwave-related deaths (%)		Severe intensity heatwave-related deaths (%)		Extreme /severe intensity heatwave-related deaths (%)		Low-intensity heatwave-related deaths (%)	
		ρ	*P-value	ρ	*P-value	ρ	*P-value	ρ	*P-value
HVI	1152	0.11	0.00	0.06	0.02	0.07	0.00	0.11	0.00
Factor 1	1152	0.19	0.00	0.14	0.00	0.15	0.00	0.18	0.00
Factor 2	1152	0.15	0.00	0.08	0.00	0.00	0.00	0.17	0.00
Factor 3	1152	−0.15	0.00	−0.15	0.00	−0.14	0.00	−0.15	0.00
Factor 4	1152	0.01	0.59	0.04	0.16	0.00	0.50	−0.02	0.59

Note: Factor 1: Less than 12-year education/low income/non-health professionals/ diabetes prevalence, Factor 2: English language not well/Not- Australian, Factor 3: Unemployed/Without homeownership, Factor 4: Living alone/ impervious surface.

Table 6
Capital cities (N = 1152 SA2s) scale linear regression analysis at 95 % confidence interval (CI) for association between one-unit increase in heatwave-health vulnerability index (HVI), the individual HVI factors, and % of heatwave-related deaths from overall heatwave, severe, extreme/severe, and low-intensity heatwave days.

Variable (Predictors)	Heatwave-related deaths (%)			Severe heatwave-related deaths (%)			Extreme/severe heatwave-related deaths (%)			Low-intensity heatwave-related deaths (%)		
	β (95 % CI)	P-value	R^2	β (95 % CI)	*P*-value	R^2	β (95 % CI)	P-value	R^2	β (95 % CI)	P-value	R^2
HVI	0.18 (0.08–0.27)	0.00	0.01	0.39 (0.05–0.74)	0.02	0.00	0.38 (0.09–0.67)	0.00	0.00	0.21 (0.09–0.32)	0.00	0.01
Factor 1	0.26 (0.18–0.34)	0.00	0.04	0.72 (0.42–1.02)	0.00	0.02	0.62 (0.38–0.86)	0.00	0.02	0.29 (0.19–0.38)	0.00	0.03
Factor 2	0.22 (0.14–0.30)	0.00	0.02	0.41 (0.11–71)	0.01	0.01	0.40 (0.16–0.65)	0.00	0.01	0.28 (0.18–0.37)	0.00	0.03
Factor 3	−0.21 (−0.29- -0.213)	0.00	0.02	−0.79 (−1.09- -0.50)	0.00	0.02	−0.59 (−0.82- -0.34)	0.00	0.02	−0.24 (−0.33- -0.14)	0.00	0.02
Factor 4	0.02 (−0.06–0.10)	0.59	0.00	0.21 (−0.08–0.51)	0.16	0.00	0.08 (−0.16–0.33)	0.51	0.00	0.03 (−0.07–0.12)	0.59	0.00

Note: Factor 1: Less than 12-year education/low income/non-health professionals/ diabetes prevalence, Factor 2: English language not well/Not Australian, Factor 3: Unemployed/Without homeownership, Factor 4: Living alone/impervious surface. Note: variance inflation factor (VIF) of 1 indicates no multicollinearity among the dependent and independent variables.

The five main findings were observed in this study: (1) we found a statistically significant association between HVI and risk of heatwave-related deaths across the capital cities (Sydney, Melbourne, Brisbane, Adelaide, Perth, Hobart, and Darwin), (2) the association between overall HVI including the individual HVI factors and the risk of deaths increases under severe heatwave days particularly within the cities, (3) factor 1 (less than 12-year education/low income/non-health professionals/diabetes prevalence) showed the strongest association with all the heatwave-related deaths across the cities, (4) we did not find an association between HVI and risk of heatwave-associated death in Australia-wide analysis, and (5) there was evidence of stronger association between factor 4 (excess heat factor/Indigenous) and heatwave-related deaths nation-wide.

Several studies have examined human vulnerability index from heat exposure and characterize the main socioeconomic factors influencing the vulnerability across Australia (Li et al., 2024; Loughnan et al., 2012; Wang et al., 2023; Zhang et al., 2018). These studies found high HVI scores in high-income residential areas (Zhang et al., 2018), densely populated areas (Wang et al., 2023), and rural areas compared to urban areas (Li et al., 2024). It was found that the Indigenous group, low English language proficiency, older people living alone, and suburban dwellers are the risk factors for heat vulnerability (Li et al., 2024; Loughnan et al., 2012). These findings coincide with this current study which found a stronger association with heatwave-related deaths and HVI factors consisting of low education, low income, and Indigenous population in Australia. Notably, the evidence of increased heat-related deaths has been well document in Australia, particularly among the elderly aged ≥65 years (Cheng et al., 2018), children aged 0–4 years (Nitschke et al., 2007; Nitschke et al., 2011), Indigenous (Quilty et al., 2023), and all age groups (Franklin et al., 2023). These findings clearly show that vulnerable populations can be identified and protected from heat-related mortality risks using HVI (Conlon et al., 2020; Reid et al., 2012).

Our findings are consistent with previous studies that reported an association between HVI and increased risk of heatwave-related deaths (Chen et al., 2016; Conlon et al., 2020; Lehnert et al., 2020; Mallen et al., 2019; Rosenthal et al., 2014). Our findings suggesting a weaker association between HVI, and heatwave-related deaths was found to be consistent with the study reported in Texas where HVI showed little association (correlation value = 0.03) with heat-related deaths using time-series analysis (Mallen et al., 2019).

A more recent study concluded that HVI was positively associated with all-cause mortality occurring during extreme heat days through the Poisson regression model in the United States, but the strength of the association was very weak (regression coefficient = 0.01) (Conlon et al., 2020). Others have also reported that increased in HVI was negatively associated with heat-related deaths across different geographical locations, indicating that vulnerability reduced risk of heat-related deaths (Chen et al., 2016; Lehnert et al., 2020). The reason for this reduced risk could be that the HVI is not predictive to increased risk of deaths in heatwave days in certain spatial areas (Reid et al., 2012). Studies that focused on individual HVI indicators such as individuals >65+ years old, income, impervious surface, and living alone, found either a weaker or non-significant association with the risk of heat-related deaths (Rosenthal et al., 2014). To some extent, these studies support our findings where our HVI was positively associated with heat-related deaths in the cities. The potential reasons are that a large proportion (about 70 %) of the Australian population living in the capital cities are highly affected by heatwaves because of heat island effect (i.e., impermeable hard surfaces such as roads, buildings, and railway lines, which has high heat absorbing capacity) (Imran et al., 2019; Razzaghmanesh et al., 2016).

The previous studies have evaluated the performance of HVI based on aggregation of health data over large geographical units (e.g., cities) to ensure high statistical power through time-series analysis. In contrast, this study focused on smaller geographical units by examining SA2-specific heat-related deaths with HVI. The reason is that HVI maps are purposely designed to help mitigate neighborhoods' (e.g., SA2s) vulnerability to heatwaves. However, for small areas such as SA2s that are generally characterized by a low count of deaths, this will cause the estimation of heatwave-related deaths to have unclear associations with large confidence intervals (Campbell et al., 2019). The above mentioned reasons explain the lack of association between HVI and heatwave-related deaths in Australia-wide analysis under this study. This is due to the presence of a large number of non-urban areas that are known to have low vulnerability to heat-related deaths compared to the greater cities (Jegasothy et al., 2017).

The previous studies validated HVI with overall heat-related health outcomes without assessing the effect of different heatwave intensities related-deaths on HVI (Kamal et al., 2021; Liu et al., 2020; Maier et al., 2014; Wolf et al., 2014). We addressed this in our analysis by modeling different heatwave intensities (extreme, severe, and low-intensity heatwaves) related deaths, and validated with HVI. Our results suggesting an association between HVI, and low-intensity heatwaves -related deaths confirm the previous evidence about the high risk of low heatwave events on increased risk of deaths and emergency presentations in Australia (Franklin et al., 2023; Wondmagegn et al., 2021). This highlights that our HVI is a good predictor of deaths occurring during overall heatwave and low-intensity heatwave conditions.

We identified several strengths in this study. First, we estimated the association between HVI and SA2-specific heatwave-related deaths across Australia using longitudinal analysis with the Quasi- Poisson regression model. This epidemiological modeling design ensured a linear association between heat-related deaths and HVI (Phung et al., 2018), allowing us to evaluate the HVI-mortality relationship with precision. In addition, conducting HVI-mortality validation at the SA2 level ensures the reliability of our model in designing a tailored SA2s level heatwave-intervention projects. Second, we validated HVI with both greater cities and across the entire Australia using nearly 20-year longitudinal mortality/heatwave data, this is the first HVI validation study with high spatial coverage. Third, the study helped to estimate the HVI-mortality association under different heatwave intensity categories.

The study was faced with several limitations. First, we validated HVI with seasonal (December–February) mortality data instead of daily data. This is due to the low count of deaths at SA2 level. Therefore, it is inaccurate to apply the HVI-mortality model with daily/weekly/monthly heatwave interventions. Second, we could not account for potential confounding variables (long-term trends, days of the week, public holidays) due to the coarse nature of our mortality data. Finally, because this is a SA2-level observational study, both causality and individual levels inference with regards to the HVI-deaths relationship cannot be claimed.

The current study has highlighted the relationship between HVI and heatwave-related deaths, this model could be assessed with daily or weekly morbidity data (hospital admissions, ambulance call-outs, emergency department visits) in the future. Considering the health effects of low-intensity heatwave events, our current HVI-death relationship highlights the need to include low-intensity heatwave days in public health interventions and adaptation programs.

5. Conclusions

Our findings suggest that the HVI scores were positively associated with heatwave-related deaths across the Australian capital cities. Although, HVI correlated with low-intensity heatwave-related deaths but showed stronger predictive ability with severe heatwave-related deaths in the capital cities. However, in a nationwide analysis, the HVI values could not predict the risk of heatwave-related deaths, which may be partly due to large number of non-urban SA2s that were protective of heat-related deaths. An HVI factor, characterized by individuals with low education, low income, diabetes prevalence, and suburbs without health professionals showed stronger association with heatwave-related deaths in greater capital cities, while HVI factor characterized by excess heat factor, and Indigenous population were better predictors of heatwave-associated deaths across Australia. This study provides evidence that HVI could reliably predict heatwave-related deaths and should be integrated into future extreme heat emergency management plans.

CRediT authorship contribution statement

Patrick Amoatey: Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing. **Ralph Trancoso:** Resources, Writing – review & editing. **Zhiwei Xu:** Supervision, Writing – review & editing. **Darsy Darssan:** Writing – review & editing. **Nicholas J. Osborne:** Supervision, Writing – review & editing. **Dung Phung:** Supervision, Conceptualization, Methodology, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107812.

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