Future population exposure to Australian heatwaves

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Abstract

Heatwaves are Australia’s deadliest natural hazard. Anthropogenic climate change has increased the intensity, frequency and duration of heatwaves over Australia in the past several decades and these trends are projected to worsen in the future. Despite the strong knowledge of heatwave characteristics and their projected changes, there remains a gap in understanding how the Australian population will be exposed to future heatwaves. This study estimates changes in future exposure to heatwaves over Australia. We find that both for continental Australia and its capital cities, the trends in exposure are not projected to increase, but accelerate in the future. For RCP4.5-SSP2 and RCP8.5-SSP5 scenarios, the mean exposure to heatwaves in Australia is projected to increase by ∼29 and ∼42 times by the end of 21st century. Sydney, Melbourne, and Adelaide are the major cities where the population is most exposed to future heatwaves, with this exposure projected to increase by 52, 61, and 56 times respectively under the RCP8.5-SSP5 scenario. The results demonstrate that anthropogenic climate change is the key contributor (over 95%) in enhancing future heatwave exposure and population change on its own plays a relatively minor role (less than 5%). The results of this study are crucial for planning where adaptation measures might be necessary to protect large group of vulnerable Australians to future heatwave exposure.

1. Introduction

The global mean temperature has warmed by 1.1 °C since pre-industrial times [1]. A direct effect from this is a subsequent increase in temperature extremes. Since the 1950s, it is virtually certain that temperature extremes have become more frequent and more intense across most land regions globally [2–4]. However, the increase is not globally homogeneous and there are significantly larger increases reported in Europe [5–7] and Australia [8, 9].

Heatwaves are a specific type of temperature extreme, commonly defined as three or more consecutive days of excessive heat [10, 11]. Climate models show that under the influence of anthropogenic climate change, heatwaves are projected to be more frequent and intense in the coming decades [1]. Heatwaves can have detrimental effects on human health, resulting in increased mortality and morbidity [12, 13]. Heatwave-related mortality and morbidity for a specific region, however, can vary significantly depending on various factors such as age, health condition, socioeconomic status, and geography [14]. For example, anthropogenic climate change in combination with urbanisation exacerbates the frequency and severity of heatwaves in cities, thus exposing larger urban populations to more heatwaves compared to rural areas [15, 16]. People with pre-existing cardiovascular and chronic respiratory conditions, as well as those with diabetes, appear more likely than other...
populations to experience mortality and morbidity because of heatwaves [17–19]. The elderly population is more vulnerable to heatwaves with 82%–92% of excess mortality occurring in this group [12], as the ability to physiologically maintain core body temperature during heatwaves becomes compromised with age [20, 21].

In Australia, heatwaves are the deadliest natural hazard, causing 55% of all-natural hazard related deaths and costing the Australian workforce ∼US$6.2 billion every year [22]. The intensity, frequency, and duration of heatwaves over Australia have increased over the past decades [23]. Climate projections demonstrate that heatwaves will further intensify across the continent throughout the end of 21st century under different emission scenarios [24, 25].

Over the state of South Australia, heatwave days (HWD) incur an increase in morbidity as compared to non-HWD across the different climatic regions [26]. Over the state of Tasmania, during heatwaves there is a surge in ambulance dispatches for the elderly, the young and those from areas of greater socioeconomic disadvantage [19].

Despite these studies examining the characteristics of heatwaves and their future projections, and impact on mortality and morbidity, there remains a gap in understanding how the Australian population is exposed to heatwaves. Past studies have shown that under the influence of anthropogenic climate change, exposure to heatwaves will also increase substantially in different parts of the globe [27, 28]. However, until now, we are not aware of any study conducted for Australia which attempts to quantify the impact of heatwaves on population exposure, either for the present or future climate. Knowing that heatwaves over Australia are more deadly than all other natural disasters combined [24], population exposure responses need their own, dedicated study over this continent.

Understanding heatwave exposure is an important first step towards estimating regional scale changes in the health risks associated with heatwaves. Exposure analysis helps quantify the relative importance of different drivers of specific risks. Understanding and projecting changes in heatwaves and corresponding population exposure is of critical importance to inform and prepare public health planning.

In this study, we have three main research objectives. First, we project the future magnitude and spatial patterns of heatwaves and exposure under different development pathways. Secondly, we examine the relative importance of climate and population changes to exposure; and, lastly, we examine how elderly (those aged 65 and over) and young (those aged below 65) population will be exposed to heatwaves in the future using fixed-age population projections across the different development pathways.

2. Materials and methods

2.1. NARClIM regional climate simulations

To analyse future projections of heatwaves, we use data from the second generation of dynamically downscaled, New South Wales (NSW) and Australian Capital Territory (ACT) (NARClM1.5) regional climate simulations over Australia [29]. NARClM1.5 is a six-member ensemble driven by two regional climate models (RCMs) and three global climate models (GCMs) (ACCESS1-3, ACCESS1-0, and CanESM2) from the Coupled Model Intercomparison Project, version 5 (CMIP5) ensemble. The two RCM configurations are distinct combinations of physics schemes of the Weather Research and Forecasting (WRF) model [30], which were selected from 36 physics scheme combinations based on model performance and independence of their errors [31]. Each N1.5 simulation was run from 1951 to 2100 continuously using a later version of WRF model (WRFv3.6 versus WRFv3.3) under the RCP4.5 and RCP8.5 emission pathways [29]. In this study, we use 50 km resolution outputs from the CORDEX domain.

2.2. Observations

We use observational data from the Australian Gridded Climate Dataset (AGCD [32]) to compare NARClM simulated heatwaves with observations. The AGCD data set has a spatial resolution of 0.05° and is obtained from an interpolation of station observations across the Australian continent. We use the conservative gridding scheme from the Climate Data Operators (CDO) [33] to re-grid the AGCD temperature data to the 50 km resolution CORDEX domain.

Comparison of NARClM1.5 to observations suggests that, although NARClM1.5 underestimates (∼3–4 days) heatwaves in northern and north-eastern parts of the domain and overestimates (∼2–3 days) heatwaves in southern and south-western parts of the domain; they reasonably capture the spatial patterns of observed heatwave characteristics (see supplement figure S1 available online at stacks.iop.org/ERL/17/064030/mmedia). Smaller biases are observed (∼1–2 days) over the highly populated south-eastern coastal regions and cities like Adelaide, Hobart, and Sydney. Some of the differences between the model simulated and observed heatwaves can be attributed to internal climate variability which is an important source of uncertainty at regional scales [34, 35]. These results are also consistent with heatwave characteristics simulated by NARClM1.0 (Herold et al [25], their figure 1) and global datasets like CMIP6 (Hirsh et al [36], their figure 1).

Model agreement with observations of historical climate provides a means to assign model confidence. Here we assert that the reasonable representation of past climate gives us confidence that
NARClM1.5 provides reliable future projections of extreme heat over Australia. However, it must be noted that these simulations are not predictions but instead are designed to show the response of the climate system to plausible scenarios of external factors that force the climate into the future, which may probably not play out exactly as specified in the emission scenario [37].

2.3. Population data
The most recent official Australian population projections are only available to 2066 [38]. Earlier projections are available through to 2101 [39], however, neither of these products provide projections at spatial resolutions suitable for our analysis. Additionally, these projections are solely based on assumptions of fertility, mortality and migration and therefore do not account for all the factors which can lead to the future population change. Hence, to estimate changes in population, we use projections based on Shared Socioeconomic Pathways (SSPs [40]). These SSPs describe five alternative outcomes for trends in demographics, economics, technological development, lifestyles, governance, and other societal factors.

The SSP scenario data provide global gridded population data at 0.5° × 0.5° spatial resolution and yearly temporal resolution. The five SSP scenarios, i.e. SSP1, SSP2, SSP3, SSP4, and SSP5 are defined as sustainability, middle of the road, regional rivalry, inequality, and fossil fuelled development. A previous study has combined RCP4.5-SSP2 and RCP8.5-SSP3 to study global exposure [27]. The SSP3 scenario envisions relatively low investments in human capital and low-income growth leading to low population growth (or decline) in countries like Australia [41]. This scenario looks highly unlikely for Australia as the Australian Bureau of Statistics consistently project future increases in Australian population [38, 39]. Therefore, we examine RCP4.5-SSP2, and RCP8.5-SSP5 to examine exposure across Australia. However, we also examine three additional combination of emissions and SSP scenario, i.e. RCP8.5-SSP3 (to compare our results with that of a past global study using the same emission scenario [27]), RCP4.5-SSP1 and RCP8.5-SSP4 (to check the robustness of our results to variation in SSPs) (see supplement figure S1 available online at stacks.iop.org/ERL/17/064030/mmedia). As with the observations, we conservatively re-gridded the population data to the 50 km resolution CORDEX domain.

We use fixed-age population distribution across the different SSPs, to get first order insight of how young and elderly population will be exposed to heatwave in future. We therefore in this study used the demographics of the young and elderly population from Australian Institute of Health and Welfare [42]. These data quantify the percentage of young and elderly population in past and their projected changes in future at a national level.

2.4. Method to calculate heatwaves
The excess heat factor (EHF) index is used globally for heatwave severity analysis, heatwave monitoring and forecasts [10, 43–45]. Epidemiological studies have demonstrated EHF severity can have strong effect on morbidity and mortality in Australia for both city and regional communities [26, 43, 46]. Multiple other studies have shown that EHF is a useful indicator to assess the effect of heatwaves on human health at a population level [27, 47].

During a heatwave, minimum temperature significantly affects the diurnal cycle of heating. High minimum temperature will result in earlier and longer sustained high temperatures with stronger heat accumulation within the diurnal heating cycle. Consequently, the average of maximum and minimum temperature is used in the EHF calculations [10]

\[ \text{EHF} = \text{EHF}_{\text{sig}} \times \max (1, \text{EHF}_{\text{accl}}). \]  
(1)

There are two components for the calculation of EHF. The first component is called the significance index (EHF_{sig}; equation (2)) and it is a measure of how hot a three-day period is with respect to an annual temperature threshold at a given location. Here, \(T_i\) represents the mean daily temperature of day and \(T_{95}\) represents the 95th percentile of all daily mean temperatures over the base period 1976–2005.

\[ \text{EHF}_{\text{sig}} = \frac{T_i + T_{i-1} + T_{i-2}}{3} - T_{95}. \]  
(2)

The second component of EHF is called as acclimatisation index (EHF_{accl}; equation (3)) and it is a measure of how hot the previous three-day period is with respect to the recent past (the last 30 days). This index is based on the consideration that people acclimatise to their local climate.

\[ \text{EHF}_{\text{accl}} = \frac{T_i + T_{i-1} + T_{i-2}}{3} - \frac{T_{i-3} + \ldots + T_{i-32}}{30}. \]  
(3)

EHF is a product of EHF_{sig} and EHF_{accl}. Equation (1) ensures that sign of EHF is equal to sign of EHF_{sig} implying that a heatwave is present if EHF is positive (but not otherwise), but if additionally, the acclimatisation (EHF_{accl}) is positive, then that property amplifies the EHF.

The EHF has units of °C² and to identify heatwave events we require that the EHF be positive for a minimum of three consecutive days. Annual total HWD is then defined as the total number of days that contribute to heatwave events in a year. Past research has also used HWD to study population exposure [27]. In this study, we use the Climapct version 3 (https://climpact-sci.org/) to calculate the heatwave properties.
Since NARClM1.5 historical simulations finish in 2005, we define our base period as 1976–2005. To capture the end of 21st century we choose the future period between 2070 and 2099. Exposure to heatwaves is calculated at each grid point by multiplying HWD and population (units of person-days). We calculate the ensemble mean (mean of NARClM1.5 simulations) of simulated HWD, population and exposure for the base and future periods. In addition to performing analysis at the continental scale, we also investigate results for all capital cities of Australia. To select the city-level data from the gridded data, we use CDO, distance-weighted average remapping i.e. ‘remapdis’ module. This module uses operators for an inverse distance weighted average remapping of the four nearest neighbour values of fields between grids in spherical coordinates. Past studies have also used the same methodology for performing city-level analysis using NARClM data.

Furthermore, we use the methodology of Jones et al. [28] and Liu et al. [27] to assess the influence of climate and population on exposure. Total exposure change is calculated as a product of climate and population projections. We then decompose the total change of exposure into three effects using equation (4): the climate effect, that is the influence of climate on exposure by allowing climate to change according to the model projections but leaving population fixed at the base period level; the population effect, that is the influence of population on exposure by allowing population to change but leaving the climate fixed at the base period level; and, the combined effect, total exposure change minus the summation of climate and population effect changes. The combined effect is a result of simultaneous variations in both climate and population where changes in climate and population do not affect each other, but their simultaneous changes affect the total exposure [27, 28]. We then calculate the contribution of each effect on the future changes in exposure for both Australia and capital cities:

\[
\Delta \text{Exposure} = \Delta \text{Exposure}_{\text{hist}} = \Delta \text{HWD}_{\text{hist}} \times \Delta P_{\text{hist}} + \Delta P \times \Delta \text{HWD}.
\]

In equation (4), \(\Delta \text{Exposure} \) is the total change in exposure calculated as difference between future (2070–2099) and base period (1976–2005). \(\text{HWD}_{\text{hist}}\) and \(P_{\text{hist}}\) are the HWD and population in base period and \(\Delta \text{HWD}\) and \(\Delta P\) are the change in HWD and population between future and base period respectively. Three terms in equation (4) represent the population effect (\(\text{HWD}_{\text{hist}} \times \Delta P\)), climate effect (\(\Delta \text{HWD}_{\text{hist}} \times \Delta P_{\text{hist}}\)) and the combined effect (\(\Delta P \times \Delta \text{HWD}\)), respectively. If we divide both sides of the equation (4) with \(\text{Exposure}_{\text{hist}}\) (the exposure in base period i.e. \(\text{HWD}_{\text{hist}} \times P_{\text{hist}}\)), the equation (5) provides an estimate of the percentage change for each effect. Here, the first, second and third term on right hand side of equation (5) denote the percentage change for climate, population, and combined effect, respectively.

So, despite different scales of population and HWD, their relative change in future determines their contribution on the exposure change:

\[
\frac{\Delta \text{Exposure}}{\text{Exposure}_{\text{hist}}} = \frac{\Delta \text{HWD}}{\text{HWD}_{\text{hist}}} + \frac{\Delta P}{P_{\text{hist}}} + \frac{\Delta \text{HWD}}{\text{HWD}_{\text{hist}}} \times \frac{\Delta P}{P_{\text{hist}}}. \tag{5}
\]

### 3. Results

Figure 1 presents the spatial distribution of HWD, population and the corresponding population exposure to heatwaves for the base and future periods for RCP4.5-SSP2 and RCP8.5-SSP5. For the base period, HWD shows small regional variance, and the entire continent typically experiences HWD between 6 and 12 days (figure 1(a)). The longest HWD (>8 days) is observed in the northern and western regions of Australia. At the end of the 21st century, HWD is projected to increase substantially in both the emission scenarios. The larger increase in HWD is projected in northern Australia. For RCP4.5 and RCP8.5, HWD is projected to increase by 9 and 20 times respectively in northern regions (figures 1(b), (c) and S2(b), (c)). By the end of the 21st century for RCP8.5, half the year (>180 days) would constitute heatwave conditions relative to 1976–2005 in northern Australia. Such a significant increase in HWD in the northern part of the domain is attributed to the smaller temperature variability of the tropics and thus the relatively minor increase in temperature needed to exceed the 95th percentile on which the EHF is based (equation (2)). Changes in HWD are not as large in southern Australia as in northern Australia, but still HWD are projected to increase by ~2 and 6 times respectively in the RCP4.5 (figures 1(b) and S2(b)) and RCP8.5 (figures 1(c) and S2(c)) emission scenarios. Along the east coast, HWD are projected to increase by ~6 and ~12 times in the RCP4.5 (figures 1(b) and S2(b)) and RCP8.5 (figures 1(c) and S2(c)) emission scenarios, respectively.

The overwhelming majority of the Australian population lives close to the coast (figure 1(d)). Under the SSP2 and SSP5 scenarios, the population is projected to increase across the continent with major increases in eastern and south-western coastal regions, where most of the Australian population currently resides (figures 1(e) and (f)). On average, Australian total population is projected to increase from ~18 million (mean population between 1976 and 2005) to between ~29 and ~40 million i.e. 1.5 and 2.2 times (mean population between 2070 and 2099) for the SSP2 and the SSP5 scenarios, respectively (figures 1(e), (f) and S2(e), (f)).
The consistent increase in HWD and population leads to large future increases in exposure (figures 1(h) and (i)). However, the rate of increase of future changes in HWD are substantially higher than population changes over the entire continent. Since exposure is calculated as a product of HWD and population, the strong increases in HWD altogether drives the future exposure changes. In comparison to the base period, there is an approximately 10–14 and 24–28 times increase in exposure for the RCP4.5-SSP2 (figures 1(h) and S2(h)) and RCP8.5-SSP5 (figures 1(i) and S2(j)) scenarios, respectively. There is also a substantial regional variation in projected total exposure, with predictably extremely high increase across most of the eastern coastal regions and less so in the western coastal regions. The northern and eastern coastal regions show greater than 18 and 37 times increase in exposure for RCP4.5-SSP2 and RCP8.5-SSP5 scenarios, respectively (figures S2(h) and (i)).

We examine the exposure changes separately for capital cities as more than 65% of the Australian population resides in these capital cities [38]. Understanding population exposure in these cities is crucial for planning where adaptation measures might be necessary to cope with heatwave exposure. We also decompose our exposure analysis to assess the relative importance of population and climate drivers (figure 2(b)). For the Australian continent, the exposure is projected to increase by ~29 and 42 times for RCP4.5-SSP2 and RCP8.5-SSP5 scenarios, respectively. The cities of Sydney, Melbourne and Adelaide show a higher rate of increase in exposure. For RCP4.5-SSP2 and RCP8.5-SSP5, exposure in Sydney is projected to increase by 17 and 52 times respectively, whereas exposure in Melbourne
Figure 2. Exposure for the Australian continent and capital cities. Here (a) shows the mean exposure for the base (1976–2005) (blue) and future periods (2070–2099: RCP4.5-SSP2 (green) and RCP8.5-SSP5 (red)) whereas (b) shows the percentage contribution of the climate, population and combined effect on the total exposure for the RCP4.5-SSP2 (green) and RCP8.5-SSP5 (red) emission scenarios.

is projected to increase by 21 and 61 times, respectively. For Adelaide, 17 and 56 times increase in exposure is projected for RCP4.5-SSP2 and RCP8.5-SSP5, respectively. The cities of Perth, Hobart, Darwin, and Canberra show between 12–17 and 38–46 times increases in the exposure for RCP4.5-SSP2 and RCP8.5-SSP5, respectively.

The decomposition of exposure into climate, population, and combined effect (figure 2(b)), reveals that, both at the continental scale and for the cities, combined (concurrent changes in population and climate) and climate effect (constant population scenario) together explains the majority of the total exposure change, whereas population effect (constant climate scenario) explains only 1%–3% of the total exposure change for both the scenarios. On average for all the regions, for RCP4.5-SSP2, climate effect typically explains ~59% of the total exposure change, whereas combined effect typically explains ~36% of the total exposure change. The contribution of the population effect is only ~5%. For the RCP8.5-SSP5, the climate effect typically explains ~44% of the total exposure change, whereas the combined effect typically explains 53% of the total exposure change. With the increases in population from SSP2 to SSP5, the contribution of combined effect increases between RCP4.5-SSP2 and RCP8.5-SSP5. Given the small contribution of the population effect across the two scenarios, it can be concluded that the change in exposure is almost entirely driven by changes in the climate at all scales. Indeed, in absence of climate change the exposure would be reduced by 97% and 96% for RCP4.5-SSP2 and RCP8.5-SSP5 scenarios, respectively.

The analysis of three additional combination of emission and SSP scenarios (RCP4.5-SSP1, RCP8.5-SSP5, RCP8.5-SSP4) also revealed that both for the Australian continent and the capital cities, the climate effect explains majority (greater than 70%) of total exposure change (see supplement). As a test for robustness, we re-did the analysis by choosing an alternate heat index (number of days greater than 35 °C) in place of HWD. The results of this analysis re-produced the key results of this paper, i.e. climate effect together with combined effect typically explains majority of the total exposure change (see supplement). These results again highlight that irrespective of the population scenario and choice of heat index used, the climate and the combined effect are always substantially larger than the population effect.
for both the Australian continent and the cities—and thus the most prominent contributor to overall change in exposure. Population on its own plays a minor role in enhancing future rates of extreme heat exposure at the population level. Past studies have also shown that globally, combined and climate effects remain the most prominent contributor to overall change in exposure and that in absence of
climate change future exposure to heatwaves would be reduced substantially [27].

To analyse the temporal trend of overall exposure changes and the contributions from climate, population and combined effects, we calculated the annual exposure from 2010 to 2099 for continental Australia and its capital cities (figures 3 and S8). For all the trends, we performed a Mann–Kendall trend test to examine their statistical significance [48]. Statistical significance was computed at the 1% level. Furthermore, we observe that total exposure trends over Australia are not only increasing but accelerating in the presence of anthropogenic climate change and remain significant starting from 2010 until the end of the 21st century. The temporal pattern of combined and climate effect follows the temporal pattern of total exposure throughout the time-period both for the continental Australia and its capital cities. Like total exposure, trends in the combined and the climate effect remain significant between 2010 to the end of 21st century, and 2050 to the end of 21st century for continental Australia and capital cities, respectively.

In comparison to total exposure, and climate and combined effects, trends in population show high variability and are not significant. The temporal analysis thus reveals the same result as climatology, i.e. the main contributor to the overall exposure in all the regions is the combined and climate effect while the population effect is small but positive. In terms of heatwave exposure, the highest total exposure by the end of 21st century is projected in Sydney, Melbourne and Adelaide (∼100 million person-days), whereas for all the other major cities exposure typically lies between 10 and 15 million person-days. This can be attributed to the comparatively higher current and future population over these regions in comparison to other regions (figure 1).

Australia’s current elderly population is projected to increase from 12% to 23% by the end of the 21st century 2100 [42]. This suggests that irrespective of the scenario selected the relative increase in population exposure for the elderly will be almost double as compared to the young Australian population. However, we acknowledge that future changes in age structure can show large variability across different SSP pathways [49] and using fixed-age population distribution for the different SSPs cannot fully capture the plausible future changes in exposure for the young and elderly population.

4. Discussion and conclusion

By employing climate data from RCMs and population data from global socio-economic models, our study presents the first comprehensive analysis of projected changes in heatwave population exposure over Australia. The results demonstrate that there will be an increase in exposure to heatwaves in Australia by the end of 21st century, however, the exposure increase is not projected to be uniform. The steepest rise is projected along the eastern coastal regions where most of the Australian population resides. This study highlights that those trends in exposure are not only increasing, but accelerating, and anthropogenic climate change is the key contributor in enhancing future rates of heatwave exposure and that population (on its own) plays only a minor role.

Our results agree with that of Liu et al [27] who showed that globally and for different continents exposure is projected to increase substantially in RCP8.5. The projected exposure changes over Australia for RCP8.5 in our study (42 times) is however weaker than what Liu et al (2017) found over Africa (118 times) but stronger than global mean (30 times) and Europe (4 times) [27]. Our results are stronger than of Jones et al [28] who using a simplified heat index (number of days with maximum temperature greater than 35 °C) found that, US population exposure to extreme heat increases four- to sixfold over observed levels in the late 20th century. The weaker projected exposure changes in Jones et al [28] can be partly attributed to the rigid choice of heat index and comparatively weaker emission scenario (SRES A2) used in that study as compared to our study. Despite the differences between the choice of heat index, models, and emission scenarios, both these studies [27, 28] and our study shows that anthropogenic climate change is the main contributor for exposure changes globally and across different geographic regions.

However, we must note certain caveats. First, the results of this study provide exposure projections at a population level, and the results do not relate to individual personal exposure. For example, population level exposure increases fastest along the heavily populated eastern coastal regions, but the individual personal exposure increases most in the northern Australia where half of the year (>180 days) constitutes heatwave conditions by the end of the century (under RCP8.5). Therefore, the results of this study are largely only relevant for region–city level planning. Second, the demographic data used in this study are national data which we apply uniformly over the continent and the SSPs. We acknowledge that the elderly demographics varies for the urban and rural areas and for the different cities and SSPs. Third, this study does not evaluate various socio-economic characteristics of the population such as different age groups, pre-existing health conditions, gender, income, or level of education. Other identified sub-groups with increased vulnerability to heatwaves include those working outdoors or in non-cooled environments. All these factors are known to impact heatwave-related mortality and morbidity [15–18]. Fourth, this study also does not address the combined effects of temperature and humidity, i.e.
'heat stress'. Future research could investigate population exposure to heat stress, which is known to have adverse impacts on human health [30, 51]. Fifth, this study uses output from single dynamical downscaling exercise. We recognise that six RCMs cannot fully represent the range of outcomes (potentially) present in the full suite of CMIP5 GCMs, however, a past study has shown that NARClIM1.5 RCMs span the entire range of projected temperature and precipitation change within the CMIP5 ensemble [29]. While GCMs capture many aspects of large-scale climate change well, studies of changes in extremes and their impact on society require finer spatial resolutions and sometimes more processes than are available in GCMs [28]. Sixth, NARClIM1.5 simulations use default data set for land use and land cover and thus do not consider urban expansion in the future projections. Although urban expansion is an important factor which can potentially affect future heatwave changes, the data for the same is not available. Despite these limitations, the conclusion of this study, that anthropogenic climate change is the key contributor in enhancing future rates of heat exposure remains robust. The results will vary quantitatively based on the choice of climate model, heat index, emission and population scenarios, however the overall conclusion that population exposure will increase and accelerate is extremely robust given its direct connection to increasing heat extremes with anthropogenic climate change, which has been robustly shown in the literature [1, 4, 9] and is supported by strong physical theory. The results of this study have important implications for populations affected by chronic heatwaves. Our results indicate where in Australia exposure is projected to increase at the fastest rate and how the exposure of the elderly population is going to increase for chronic heatwaves. This information is crucial for planning where adaptation measures might be necessary to cope with heatwave exposure. For instance, improvements in infrastructure, such as housing and air conditioning, together with socio-economic changes and better health care and services, will help in combatting the increasing burden of heatwaves. Specific public health interventions can play a crucial role in limiting the impacts of heatwaves, for instance by increasing the awareness of the health risk associated with exposure, and thus fostering behavioural changes or other adaptation strategies.

Data availability statement

NARClIM1.5 data that support the findings of this study are available via the following link (https://climatedata.environment.nsw.gov.au/). Data from AGCD are available freely at the Bureau of Meteorology website (www.bom.gov.au/climate/data/). Population data is available from the SEDAC website (https://sedac.ciesin.columbia.edu/).

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Conflict of interest

The authors declare no competing interests.

Author contributions

Nidhi Nishant conducted all the analyses and led the writing of the paper. All the other co-authors assisted in interpretation and writing the paper.

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