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Power outages during heatwaves: Predicting mortality burden in Australian cities

a discussion paper

Funding declaration

Written under contract for AEMO to investigate additional mortality that could be expected on the third day of an extreme heatwave in major Australian cities if power supply ceased. Daily mortality was the highest temporal estimate possible due to a lack of literature to support estimates at finer resolution.

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1 Abstract

Heatwaves are associated with significant increases in population mortality and morbidity in Australia and represent a growing threat to the health of the Australian population. High temperatures can overcome human thermoregulatory processes, leading to a spectrum of heat-related illnesses ranging from mild conditions, such as heat stress, to life-threatening heat stroke. Deaths can also occur due to exacerbations of existing illnesses, or linked to accidental causes. The risks depend on a range of inter-related physiological, contextual, and social factors. To a large extent the Australian population is well acclimatized to warm to hot summers, due in part to the high prevalence of air-conditioning (AC). However, this reliance on AC places high demands on power supply and historically has contributed to system failures.

In this discussion paper we estimate the additional mortality burden that could have resulted in the event of power outage and loss of AC during an extreme heatwave scenario in three Australian cities (Adelaide, Melbourne, and Brisbane). Specifically the effects on the third day of an extreme heatwave are considered, because this time can represent peak heat exposure and mortality. We use a definition for extreme heatwave based on the Bureau of Meteorology excess heat factor (EHF) severity categories which are applicable over broad spatial scales. Our estimates are based on published heatwave mortality data and conservative estimates for the health protective effects of air-conditioning.

We conclude that loss of AC for a single day in an extreme heatwave scenario could have resulted in 10-21 additional deaths in Adelaide (in 2009), 24-47 in Melbourne (in 2014) and 7-13 in Brisbane (in 2004). We discuss the limitations to these estimates, related to the availability of published heatwave mortality data and limited evidence to quantify the protective effects of AC in Australian settings.

2 Introduction

It is well documented that mortality and morbidity increase during extreme heat events in Australia, and in relation to increasing daily temperatures. Heat-related health effects arise when an individual's thermoregulatory capacity fails to maintain a core body temperature (36.0 to 37.5^{o}C) due to high ambient temperature. The spectrum of heat-related illness ranges from mild conditions, such as heat stress or heat exhaustion, to life-threatening heat stroke.(1) Heat can also exacerbate existing illnesses, particularly cardiovascular, respiratory, and renal conditions.(2) These effects can have rapid onset and can result from dehydration due to increased sweating. In addition, heat-induced fatigue may be responsible for increased risk of motor vehicle and other accidents.(3)

Mortality due to heatwaves can be difficult to measure, as deaths can be due to direct heat-related conditions (such as heat stroke) or related to underlying chronic conditions or other causes. Excess mortality is commonly used as a measure of impact of specific events. It is estimated by comparing the mortality during the heatwave event with equivalent time periods prior to the event. It should be noted that estimates for excess mortality can differ from other measures of impact, for example heat-related deaths as determined by the state coroner or pathologist.

In Australia, notable heat events resulting in excess mortality are: Brisbane 2004 (75 excess deaths)(4); Melbourne 2009 (374 excess deaths)(5); Adelaide 2009 (32-35 estimated excess deaths(6, 7); 58 heat-related deaths(8, 9)) and 2014 (38 excess deaths)(7); Sydney 2011 (96 excess deaths).(10) In general, excess mortality is only evident during the more severe or extreme heatwaves at any location.(11)

Heatwaves disproportionately harm vulnerable groups. The elderly, infants, and those with pre-existing illness can be vulnerable by virtue of their physiology, while others may be vulnerable due to social factors, such as low socioeconomic status and housing disadvantage. Workers or others who undertake physical activity in the heat without adequate precautions can also be at high-risk.[12, 13]

Access to air-conditioning is a protective factor during heatwaves and ABS data from 2014 indicates that 74% of Australian households use AC for cooling.[14] This is notably lower in Tasmania, where 48% of households do <u>not</u> use air conditioning, compared to only 8% in South Australia and 4% in the Northern Territory. Reliance on air conditioning is expected to rise further with increasing urban density, the loss of green canopy, and the greater retention of heat load or the urban heat island (UHI) effect. Well-designed buildings with passive cooling are not standard in most Australian cities, therefore a lack of access to home AC is assumed to put individuals at higher risk. Notwithstanding the high prevalence of AC in most Australian states, the increasing frequency and magnitude of extreme heat events has the potential to disrupt and affect the whole population, through interruptions to heat sensitive infrastructure, particularly power supply.

The purpose of this discussion paper is to consider the additional mortality burden that could be expected in the event of total power outage and loss of AC during an extreme heatwave scenario in major Australian cities. In the first section of the paper we discuss heatwave severity as a determinant of mortality and provide a definition for extreme heatwave that can be consistently applied across different locations, based on the Bureau of Meteorology excess heat factor (EHF) metric. We then provide an overview of the epidemiological evidence for the health protective effects of air-conditioning during heatwaves. Finally, we draw on this evidence and published heatwave mortality data to estimate the additional mortality burden that could have resulted from a power outage on the third day of an extreme heatwave scenario for Adelaide, Melbourne, and Brisbane. The assumptions, reasoning and limitations underlying these estimates are discussed. The paper is structured in the following sections:

1. Heat as a determinant of excess mortality
2. The protective effects of air-conditioning during heatwaves – an overview of the epidemiological evidence
3. Estimating the additional heatwave mortality due to power outages to major Australian cities.
4. Conclusions, limitations, and considerations for further research

3 Heat as a determinant of excess mortality

Heat and mortality

The impacts of heat are highly location dependent and reflect population adaptation to the local climate. In general, excess mortality is only evident during the more severe or extreme heatwaves at any location, while excess morbidity is evident during lower severity events.[11, 15] While increased mortality can occur on the same day, or following a short lag (1-day) relative to heat exposure,[16] a peak of mortality is often observed several days into extreme heatwave events (see Figures 3-1 and 3-2), and modelling indicates that some effects can be delayed up to weeks following exposure.[17]

Figure 3-1. Daily number of deaths, minimum and maximum temperatures during the 2009 heatwave (26 January-7 February 2009) in Adelaide. Reproduced from Nitschke et al (2011)[(6)]

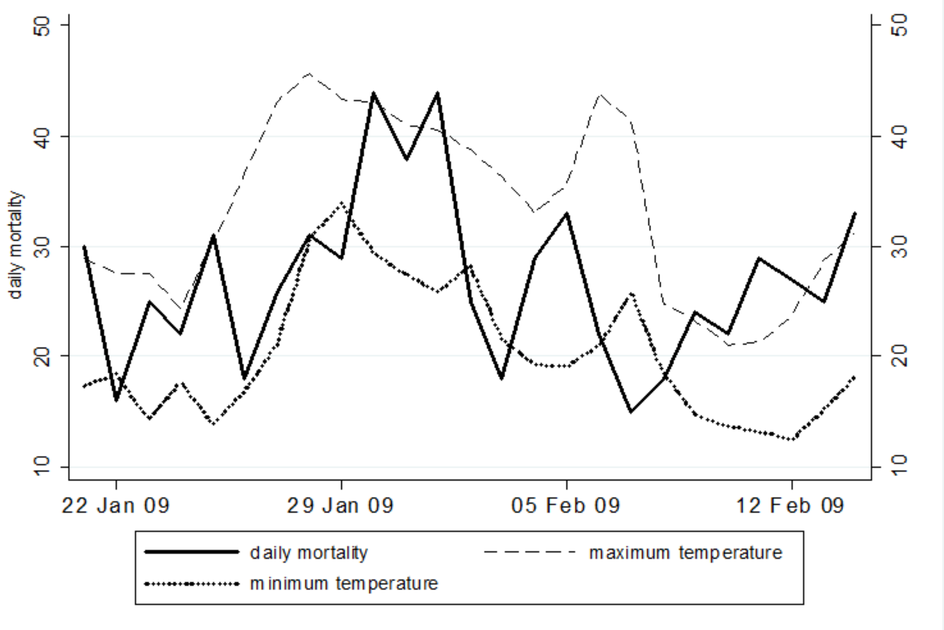
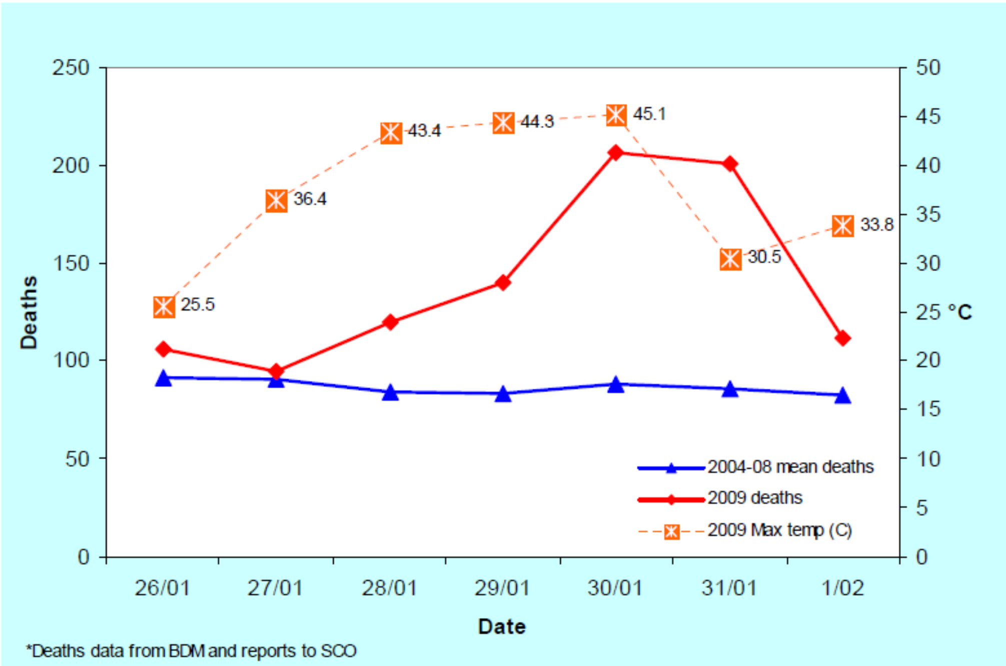


Figure 3-2. **Daily number of deaths and maximum temperatures between 26 January and 1 February 2009, compared to mean deaths 2004-08, Melbourne. Reproduced from the Victorian Chief Health Officer Report (2009)[(6)]**



Comparing or predicting the mortality burden during heatwaves is problematic because each event is a unique meteorological phenomenon, with a specific location or context. Heatwave characteristics that may influence mortality include:

- *Severity* of both maximum and minimum temperatures relative to seasonal averages. Critically, the minimum or overnight temperatures will determine the extent to which heat is dissipated overnight and therefore the accumulating thermal load impacting on vulnerable people and systems.[18]

- *Duration* will also determine cumulative heat retention in homes and urban infrastructure and it is likely that prolonged heatwaves will overcome population acclimatisation and adaptation measures.
- *Humidity* can impede evaporative heat loss through sweating and exacerbate the effects of high ambient temperature.
- *Heat impost relative to recent exposure* is also important. For example, heatwaves occurring earlier in the summer season can have greater health impacts, possibly because of insufficient time for acclimatisation and by hastening the deaths of particularly vulnerable individuals.[19]

Notwithstanding the complex nature of individual events, the Bureau of Meteorology has developed a universal metric - the ***excess heat factor*** **–** to allow comparison or ranking of heatwaves according to a common severity scale.[18]

The excess heat factor (EHF)

EHF is a unique measure of heatwave intensity that accounts for local climate and adaptation.[20] The metric is calculated using the averaged maximum and minimum temperatures (ADT, average daily temperature) over a three-day period. By comparing the 3-day average to recent and long-term averages at each locality, the short and long-term temperature anomalies are estimated and factored together to generate a measure of heatwave intensity.[21] This is outlined in Box 1.

Although humidity is not explicitly factored into the EHF estimation, the inclusion of the minimum temperature acts as a proxy for the presence of humidity (higher minimum temperatures are induced by a humid atmosphere).[18] Similarly, the temperature anomaly relative to recent (30-day) averages acts as a proxy for seasonality, such that early heatwave events will show a greater anomaly relative to recent averages.

EHF severity index

EHF intensity has been demonstrated to be applicable over broad spatial scales.[22] Comparison between locations is facilitated by conversion of EHF intensity to a severity index, comprising low, severe, and extreme categories.[18] A positive EHF intensity defines a heatwave at any location. A ***low intensity*** event is defined by EHF intensity up to the 85th percentile of each location's heatwave intensity climate record. A measure of EHF intensity over this threshold defines a ***severe*** event, and over 3 times the 85th percentile meets the threshold for an ***extreme*** event. These categories are summarized further in Box 1.

Australian counts of extreme and severe heatwaves since 2000/01 are displayed in Figure 7-4 and Figure 7-5 respectively (Appendix). Whilst this discussion paper is focused on extreme heatwaves, the higher prevalence of severe heatwaves is worth noting, due to rising mortality for over 65 year old people during severe heatwaves[18].

Box 1. The Excess Heat Factor (EHF) and EHF Severity Index

The Excess Heat Factor considers a 3-day average of daily mean temperature in relation to:
(i) The 95th percentile of long-term average temperature, representative of a location's unique climatology of heat
(ii) The average daily mean temperatures over the past 30 days, representative of the short-term temperature anomaly or recent thermal acclimatisation.

The EHF severity index captures the relative ranking of the calculated EHF metric on the distribution curve for that location. A simple classification scheme has been developed to categorise heatwave intensity relative to local climate and based on EHF values.

Low intensity heatwaves have a positive EHF value up to the 85th percentile of the EHF distribution (EHF_{85}) (EHF severity <1)

Severe intensity heatwaves are those events with $EHF \geq EHF_{85}$ (EHF severity≥1 & <3)

Extreme heatwaves are defined as $EHF \geq 3 \times EHF_{85}$ (EHF severity≥3)

By incorporating both long-term average temperatures and an acclimatisation factor in the calculation, the EHF severity index enables general application across different climatic regions, in contrast to other heatwave definitions.

EHF severity and mortality

Heatwaves in the extreme category (EHF severity>3) are infrequent events but have typically been associated with a significant mortality burden. Table 1 shows the frequency of these heatwaves since 2000 in four Australian capital cities, with estimates for the associated excess mortality and sources (where available). "Unpublished" impact events in Table 1 may have been overlooked due to shortness or possible limited impact area, overshadowed by larger proximate events or too recent for publication.

Epidemiological studies have also demonstrated that EHF severity correlates with human health impact in various locations in Australia [17, 23, 24] and overseas.[22] On the basis of this evidence, the EHF is being adopted by emergency and health agencies in most Australian states and territories to underpin their heat health warning arrangements.

Table 1. Dates, EHF severity ratings, and mortality burden for extreme events

EHF_Date	End_Date	Adelaide	Melbourne	Sydney	Brisbane	Health Impact Publications
19/01/2000	21/01/2000				4.9	22 deaths/350 injuries (EMA database)*
20/01/2000	22/01/2000				4.7	
24/12/2001	26/12/2001				3.1	7 deaths/700 injuries (EMA database)*
6/01/2004	8/01/2004				3.2	Not published
19/02/2004	21/02/2004				4.5	75 excess deaths estimated (Tong et al[4])
20/02/2004	22/02/2004				5.1	
21/02/2004	23/02/2004				3.5	
27/01/2009	29/01/2009	3.9	3.9			32-35 excess deaths estimated in Adelaide (Nitschke et al[6, 7])
28/01/2009	30/01/2009	3.6	5.7			58 heat-related deaths reported in Adelaide (Herbst et al[9]; Langlois et al[8])
29/01/2009	31/01/2009		3.1			374 excess deaths estimated in Melbourne (Victorian Chief Health Officer Report[5])
1/02/2011	3/02/2011			3.3		96 excess deaths estimated (Schaffer et al[10])
3/02/2011	5/02/2011			3.2		
2/01/2014	4/01/2014				3.1	
3/01/2014	5/01/2014				3.9	Not published
13/01/2014	15/01/2014		3.8			38 excess deaths estimated (Nitschke et al[7]), 167 excess deaths estimated (Department of Health[25])
14/01/2014	16/01/2014	3.5	5.9			
15/01/2014	17/01/2014		4.6			
17/12/2015	19/12/2015		3.1			Not published

*Historical accounts of national heatwave disasters dating back to 1895 are provided in the Emergency Management Australia disasters database.[26]

By examining the relationships between EHF severity and mortality in different cities, EHF severity has been shown to be an accurate 2-3 day lead indicator for heat-related mortality in all locations.[22] This is because EHF severity can be configured for a 3-day forward looking period, and the peak mortality typically occurs on the last day (day 3) of the exposure period. Figures 3-3,4,5 illustrate how peak EHF severity preceded peak mortality by 2 to 3 days during extreme heatwaves in Adelaide, Melbourne, and Brisbane. Similar relationships were observed during extreme heatwaves in London, Chicago, and Paris (see Appendix).

Figure 3-3. Daily EHF severity and state pathology reported heat-related deaths, January 2009, Adelaide, Langlois et al, 2013[8]. Blue line heatwave severity, black line heat-related deaths.

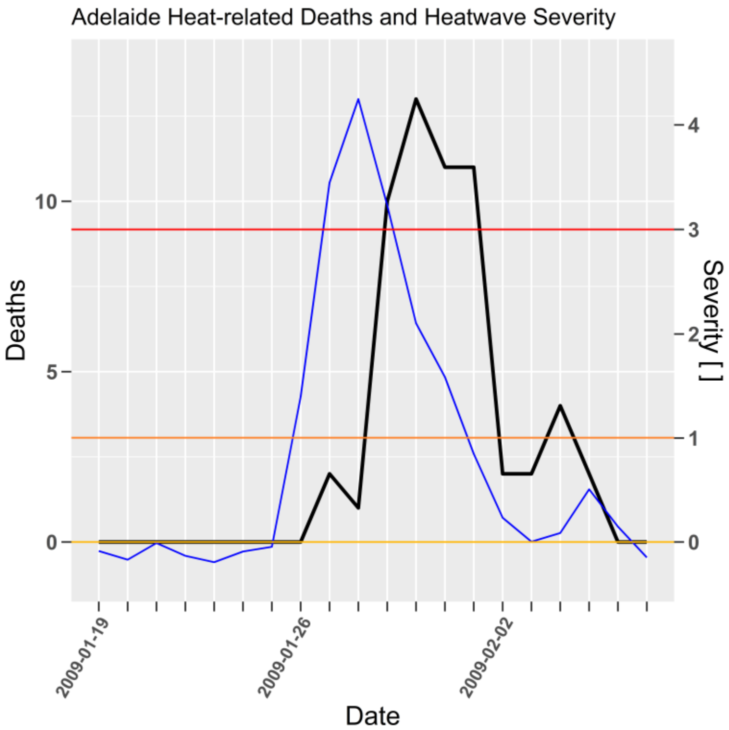


Figure 3-4. Daily EHF severity and estimated excess mortality, January 2009, Melbourne, estimated from Victorian Chief Health Officer, 2009[5]. Blue line heatwave severity, black line excess deaths.

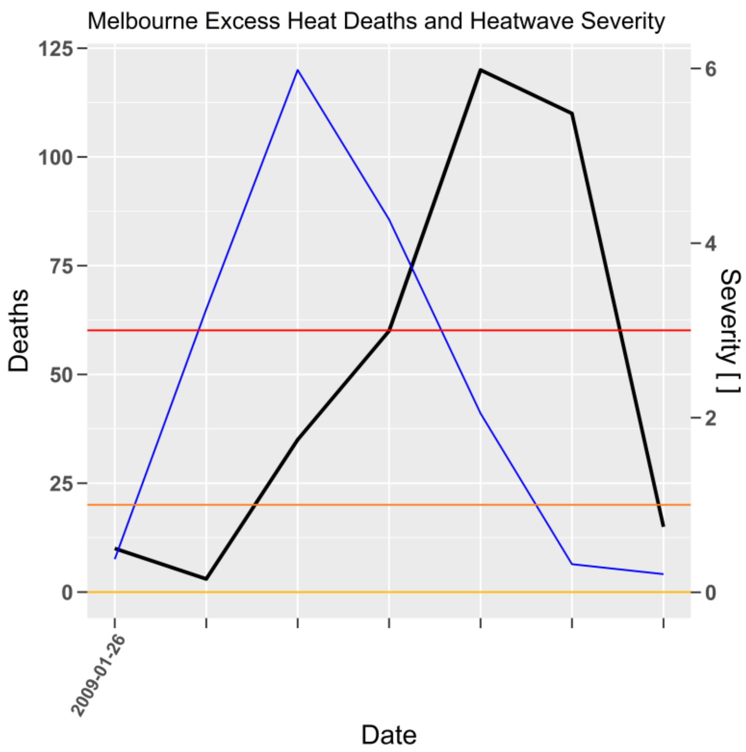
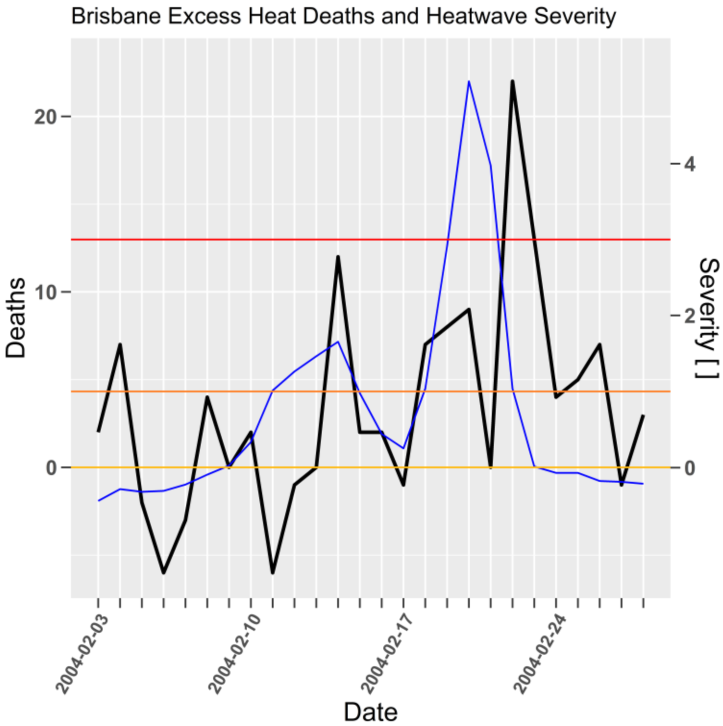


Figure 3-5. Daily EHF severity and estimated excess mortality, February 2004, Brisbane – daily mortality estimated from Tong et al [4]. Blue line heatwave severity, black line excess deaths.



4 The protective effects of air-conditioning during heatwaves: an overview of epidemiological evidence

Studies undertaken in the US and Europe have consistently shown a protective effect of air-conditioning (AC) during heatwaves. There is only one study, conducted in Adelaide, which provides evidence for an Australian population.[27] Quantitative estimates of the effect of AC vary between studies and the different contexts and study designs make it difficult to generalise the findings across locations.

Population level (ecological) studies:

Whole-of-population studies, predominantly from the US, have reported greater heat-related mortality in geographical regions with lower AC prevalence.[28-32] These ecological studies use population level mortality data and the representative measures of heat exposure and AC prevalence are assigned over large-scale geographic areas. The studies provide an indication of the protective effect of AC, but they do not account for the wide variation in individual exposure and AC use. A study in California by Ostro et al[33] found that ownership and usage of AC mitigated the association between temperature and hospital admissions (respiratory, cardiovascular, dehydration and heat stroke). This study used data at the zip code level, providing a finer spatial representation of temperature exposure and AC prevalence.

No population level studies have empirically examined the moderating effect of AC on heat-related mortality or morbidity in Australia.

Evidence from Cohort and Case-Control studies:

In a cohort study of over 72,000 US residents, death rates during hot weather (1980-1985) were found to be 42% lower among people with central AC compared with people with no AC.[34] The AC benefits were highest for women, the elderly, and people not in the labour force, consistent with the higher potential exposures of these groups to home AC.

Further evidence for the protective effects of AC has come from case-control studies, which examine individual AC use among those who are hospitalised or die during heatwaves compared with individuals who do not. While these studies assign AC use at an individual level, the findings are highly dependent on the study design, including sample size, type of analysis, and the specific outcomes examined.

Bouchama et al[35] conducted a meta-analysis of the findings from six case-control studies of heat-related deaths, conducted in U.S.A. (4 studies) and France (2 studies). The results from individual studies ranged from a 15% (St Louis, Kansas City) to 88% (Chicago) reduction in the risk of heat-related mortality associated with a working home AC (see Table 2). The variation in results is unsurprising considering the different contexts, heatwave intensities, population demographics, housing, and AC usage in each study location. By pooling the results of these studies, Bouchama et al estimated a 77% reduction in the risk of heat-related mortality associated with a working home AC.

The only case-control study from Australia was conducted following the 2009 heatwave in Adelaide.[27] Several variables relating to AC (having a home AC, AC in a bedroom, and use of AC) were found to be associated with a reduced risk of mortality during this event. Air conditioning in the bedroom was associated with a marked risk reduction (>99%) after adjusting for the influence of other variables.

Comparing these different estimates for the protective effects of AC is further complicated by the fact that the exposures are unique to each study. As the severity of heatwave exposures increase, it might be expected that the protective effects of AC would also increase.

Table 2. Estimates of the protective effects of AC from case-control studies

Location and heatwave (year)	Outcome assessed	No of cases	Risk reduction (%)	Reference
US (St Louis and Kansas City, MO) 1980	Fatal heatstroke	73	15% (10-20%)	Kilbourne et al[36]
US (Chicago, IL) 1996	Heatwave related deaths	339	80% (70-90%)	Semenza et al[37]
US (Cincinnati, OH) 1999	Heat related deaths	17	97% (80-100%)	Kaiser et al[38]
US (Chicago, IL) 1999	Heat related deaths	63	88% (70-100%)	Naughton et al[39]
France 2003	Heatwave related deaths	259 (>65yo)	51% (0-90%)	Bretin et al[1]
France 2003	Heatwave related deaths	314	80% (50-90%)	Lorente et al[2]
Australia (Adelaide) 2009	All cause mortality	82	>99% (72-100%)#	Zhang et al[27]

Adapted from Bouchama et al 2007[35]
#Result for AC in bedroom

[1] Bretin et al 2004 Bretin P, Vandentorren S, Zeghnoun A, Ledrans M. Etude des facteurs de de´cès des personnes aˆge´es re´sidant à domicile durant la vague de chaleur d’aouˆt 2003. Institut de Veille Sanitaire (InVS) Web site. http://www.invs.sante.fr/publications /2004/chaleur2003_170904/rapport_canicule.pdf. Accessed May 26, 2005.

[2] Lorente et al 2005 Lorente C, Serazin C, Salines G, et al. Etude des facteurs de de´cès des personnes aˆge´es re´sidant en e´tablissement durant la vague de chaleur d’aouˆt 2003. Institut de Veille Sanitaire (InVS) Web site. http://www.invs.sante.fr/publications/2005/canicule_etablissement/rapport.doc. Accessed May 26, 2005.

Case studies of AC in nursing homes or hospitals:

A number of case studies in the US and Europe have specifically examined the benefits of AC for populations within nursing homes or hospitals (see Box 2), and have indicated significant protective effects during heatwaves.

Box 2: Studies of AC in nursing homes or hospitals

New York: Marmor[40] examined deaths occurring in nursing homes in NY, comparing facilities with AC (n=11) to those without (n=9). Using mortality data during 4 heatwaves, he estimated a 2.2 fold increase in risk of death in un-air-conditioned homes, and an excess 94 deaths for these events. The 4 heatwaves in the study period were relatively mild, and the death rates in homes without AC could possibly reach higher levels during more severe heat waves.

Florida: A case study by Sullivan-Bolyai et al[41] investigated the deaths of elderly residents in a Florida nursing home during a 5-day period of AC failure. Of 89 residents, 21 experienced a sudden onset of fever with no accompanying symptoms, and of these 5 died. From a detailed clinical investigation that excluded other potential causes of death, such as infection, it was concluded that the deaths were due to hyperthermia as a consequence of AC failure. Notably, the residence had no alternative mechanism for cooling and most windows could not be opened. The only recorded temperature within the home during that period was 31.7^{o}C.

Portugal: In a study involving 41 hospitals, Nunes et al[42] found that the presence of air conditioning in hospital wards was associated with an increased survival of patients admitted before the beginning of the 2003 heatwave in Portugal. The reduction of the risk of dying was estimated to be 40% (95% CI 3% to 63%).

Influence of Reduced Electricity Consumption: Evidence from the Fukushima disaster

The March 2011 earthquake and tsunami disaster in Japan devastated several power stations and led to severe electricity shortages in some regions. A strategy for reduced electricity consumption, with a target of 15% of the previous summer level, was implemented for the Tokyo metropolitan region. A government campaign was launched to advise residents how to protect their safety during hot weather while minimising power use. Household electricity consumption was reduced by up to 18%, and an assessment of heat-related mortality before and after this period concluded that there was no adverse impact on the affected populations, suggesting that levels of AC use could be reduced without risk to public safety in this context.(43)

5 Estimating additional heatwave mortality due power outages in major Australian cities

As outlined in Section 4, there is scant evidence quantifying the protective effect of AC during heatwaves for Australian populations. Estimates from the international literature can be applied to Australian cities, with the caveat that these estimates are highly dependent on context. Broome and Smith[44] estimated the potential additional deaths that could have resulted from a power outage during the 2009 Melbourne heatwave, based on an AC prevalence of 73%, and using the estimate for the protective effect of AC derived from Bouchama et al[35] (77% reduction in mortality risk associated with AC). For an outage over the full 7 days, they estimated an additional 192 deaths, with a cost of $356 million for the potential excess loss of life. A single day power outage could have resulted in an additional 28 deaths. These predictions led the authors to conclude that power should never be deliberately cut-off during heatwaves to reduce bushfire risk, because any benefit could be outweighed by the increased health risks.

We have followed a similar approach to estimate the potential additional deaths for three cities, Adelaide (2009), Melbourne (2009 and 2014) and Brisbane (2004), in the event of power failure and loss of AC during these extreme heatwaves. We have specifically considered the potential effects of power loss on day 3 of these events, when both exposure and mortality typically peak (as outlined in Section 3). Our estimates (Table 3) are based on published heatwave mortality data and using ABS estimates for state AC prevalence.[14] We have considered a range of estimates for the protective effect of AC (40%, 50%, 80% reduction in mortality risk). These estimates are consistent with the range of protective effects reported in the literature (reviewed in Section 4).

Table 3. Predicted additional mortality due to power loss on day 3 of extreme heatwave scenarios (EHF severity>3) for Adelaide, Melbourne and Brisbane

Heatwave event (scenario)	EHF severity (Days 1-3)	Peak excess mortality & date (Day 3)	Proportion population with AC	Additional daily deaths		
				% reduction in mortality risk		
				40%	50%	80%
Brisbane 2004	5.1	21 (22 Feb)	77%	7	8	13
Melbourne 2009	5.7	125 (30 Jan)	79%	40	49	79
Melbourne 2014	4.6	75 (17 Jan)	79%	24	30	47
Adelaide 2009	3.6	28* (30 Jan)	92%	10	13	21

*28 excess deaths (estimated as observed daily deaths – mean of last 5 years). This differs from state pathology reported heat-related deaths for this date (shown in Figure 3-3)

6 Conclusions, limitations and considerations for further research

Conclusions

From our review of the current evidence, we conclude that loss of power and AC for a single day in an extreme heatwave scenario in Adelaide, Melbourne or Brisbane will likely result in additional loss of life. We estimate that a single day power loss occurring on day 3 of extreme heatwaves could have resulted in 10-21 additional deaths in Adelaide (2009, pop=1.2 million), 24-47 in Melbourne (2014; pop=4.3 million) and 7-13 in Brisbane (2004; pop=1.8 million). These estimates are based on: (i) the published data for heatwave deaths on day 3 of these extreme heatwaves (EHF severity>3); and (ii) a 40-80% reduction in mortality risk associated with AC. This range was chosen based on the measures for the protective effects of AC reported in the literature (discussed in Section 4).

Using mortality data from the 2009 heatwave in Melbourne, we estimated 40-79 additional deaths from a single day power outage, compared to 28 additional deaths estimated by Broome and Smith[44] for the same event. The difference is likely explained by the fact that our estimate was based on the day 3 peak mortality, while Broome and Smith considered average mortality over the 7 day event. Using mortality data from the 2014 heatwave in Melbourne, we estimated 24-47 additional deaths. Mortality was reduced in the 2014 event, compared to 2009, possibly due to implementation of the heatwave plan in Victoria.[25] Therefore the lower estimate (24-47) is more likely for future heatwave scenarios in Melbourne. Notably, this is the expected additional mortality arising on day 3 of an extreme heatwave. No attempt has been made to estimate additional lagged mortality. Our estimates reflect the populations of the three cities at the time of the extreme heatwave events and are likely to underestimate the mortality impact for populations in future events. Conversely, it is possible that public health interventions and community adaptations will moderate the impact, as described above in relation to the 2014 heatwave in Melbourne.[25] There is also evidence of reduced heatwave morbidity in 2014 compared to 2009 in Adelaide, however mortality was not reduced.[7]

Limitations

Our estimates are limited to extreme heatwaves with published daily mortality data. Total mortality estimates have been published for other heatwaves (for example, Sydney 2011) but for the purpose of this paper we needed daily mortality data to estimate the effects for a single day power outage on the third day of an extreme heatwave.

Quantitative estimates for the protective effect of AC are lacking in Australian settings, with the exception of the study by Zhang et al,[27] which suggested almost 100% reduction in mortality risk associated with AC in the bedroom. We chose a more conservative range of estimates (40-80%) to be consistent with the evidence from other published studies.

Our estimates for additional mortality do not consider the broader impacts of power outages on public safety. For example, the potential failure of communications and other infrastructure, home medical devices, and other cooling devices (fans) during heatwaves.

Within day impact estimates for power outages of differing length have not been found in the literature. Daily human health impacts are common in the literature.

Finally, our estimates are based on mortality during previous heatwave events, and past experiences may not be a reliable indicator for future heatwaves of increasing severity.

Future research

Estimating the mortality due to power outages would benefit from further research to quantify the protective effects of AC during heatwaves in Australia - using comprehensive daily mortality (and morbidity) data and incorporating spatial data for power outages.

Sub-daily human health impact could be achieved through detailed study design, although ethical barriers may be encountered due to the high likelihood that individuals are more likely to identified.

Further research should also consider the influences of changing population demographics (vulnerability), adaptation, and climate change projections.

7 Appendix

Figure 7-1. Daily EHF severity and estimated excess mortality, July 1990, London from Nairn et al, 2018[(22)]

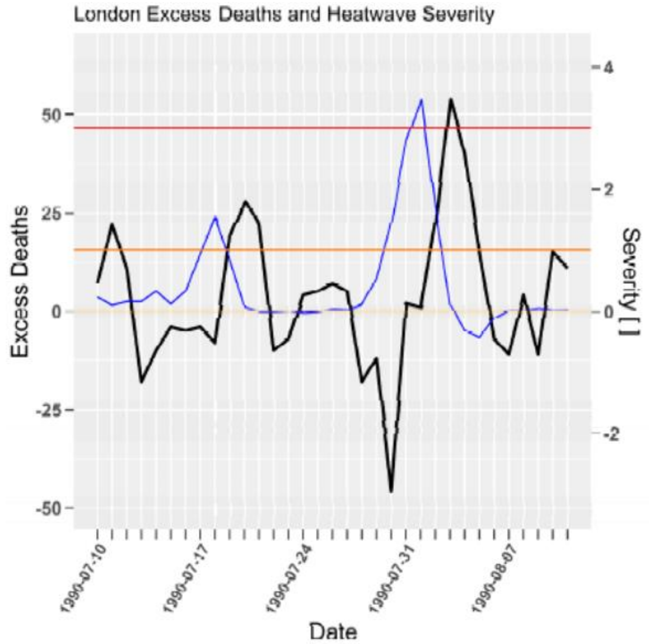


Figure 7-2. Daily EHF severity and estimated excess mortality, July 1995, Chicago[22]

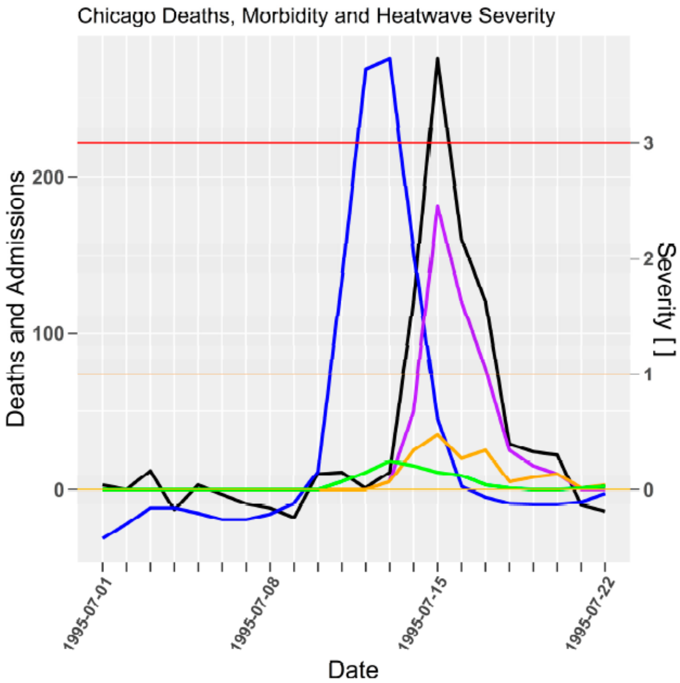


Figure 6. Chicago severity (blue), excess all cause deaths (black) (Whitman et al. [36] (p. 1517, Figure 2)), heat related mortality (purple) (Whitman et al. [36] (p. 1516, Figure 1)), heat deaths (gold) (Kaiser et al. [37] (p. S159, Figure 1)), and intensive care admissions (green) (Dematte et al. [38] (p. 174, Figure 1)) for 1995 heatwave. Daily deaths and admissions, and severity [] on left and right *y*-axes respectively.

Figure 7-3. Daily EHF severity and estimated excess mortality, August 2003, Paris/France[22]

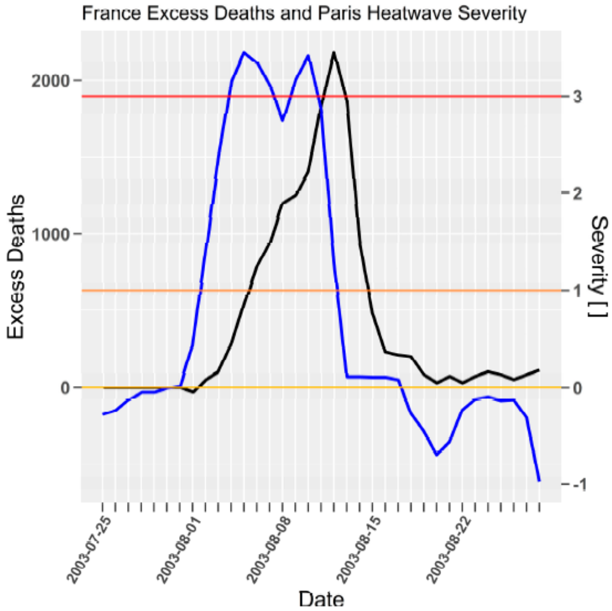


Figure 7. Paris severity (blue) and France excess mortality (black) for 2003 heatwave. Daily excess deaths (Poumadère et al. [39] (p. 1486, Figure 1)) and severity [] on left and right *y*-axes respectively.

Figure 7-4. Annual warm season counts of extreme heatwaves, 2000/01 to 2018/19.

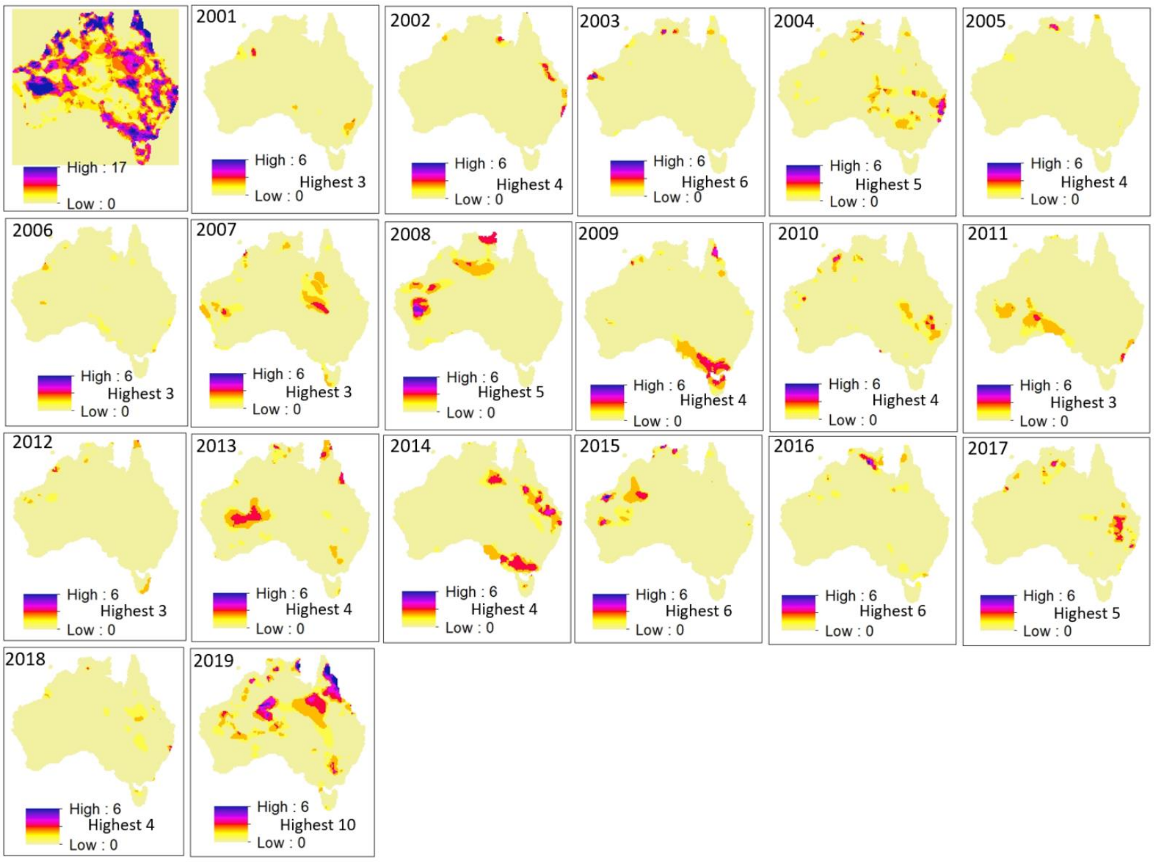
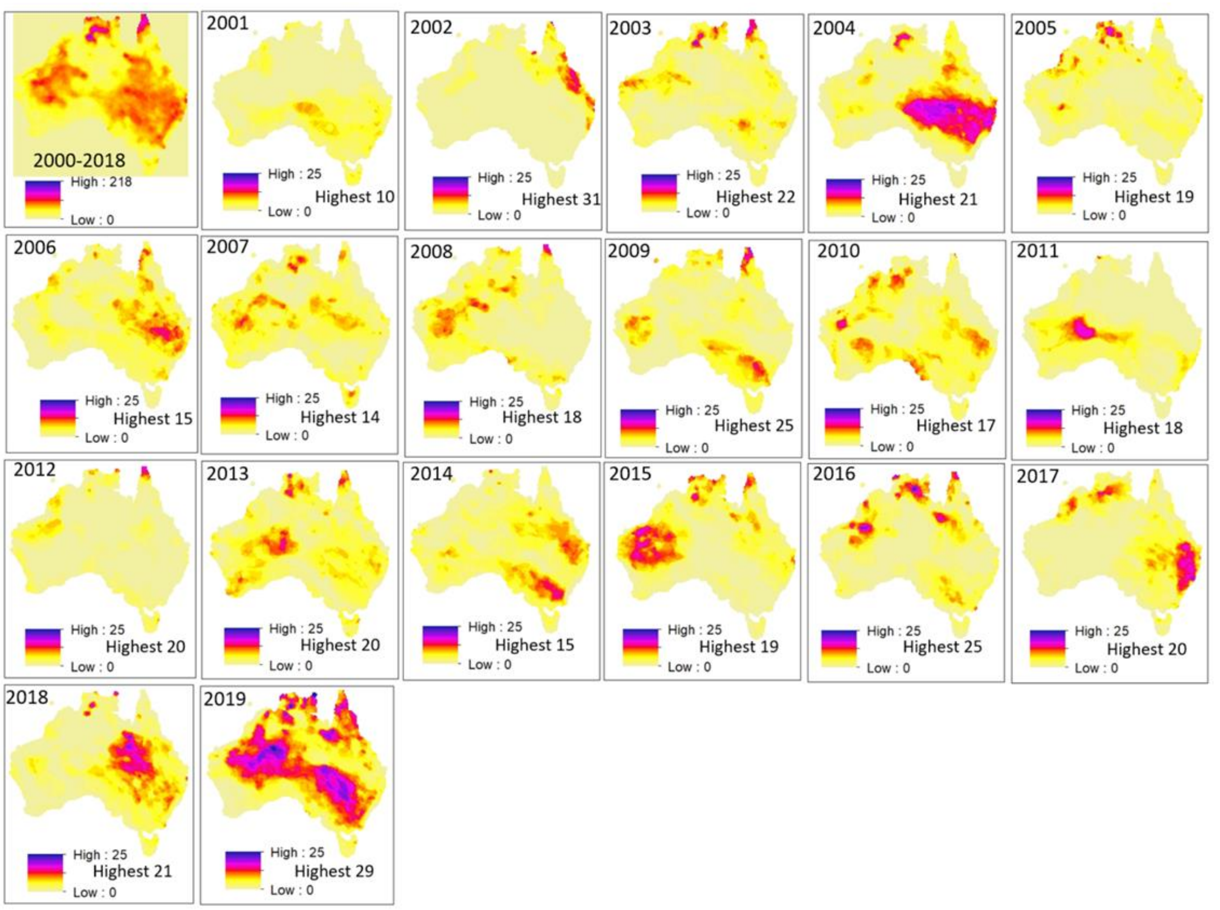


Figure 7-5. Annual warm season counts of severe heatwaves, 2000/01 to 2018/19.



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