The relative value of sociocultural and infrastructural adaptations to heat in a very hot climate in northern Australia: a case time series of heat-associated mortality

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Summary

Background Climate change is increasing heat-associated mortality particularly in hotter parts of the world. The Northern Territory is a large and sparsely populated peri-equatorial state in Australia. The Northern Territory has the highest proportion of Aboriginal and Torres Strait Islander people in Australia (31%), most of whom live in remote communities of over 65 Aboriginal Nations defined by ancient social, cultural, and linguistic heritage. The remainder non-Indigenous population lives mostly within the two urban centres (Darwin in the Top End region and Alice Springs in the Centre region of the Northern Territory). Here we aim to compare non-Indigenous (eg, high income) and Indigenous societies in a tropical environment and explore the relative importance of physiological, sociocultural, and technological and infrastructural adaptations to heat.

Methods In this case time series, we matched temperature at the time of death using a modified distributed lag non-linear model for all deaths in the Northern Territory, Australia, from Jan 1, 1980, to Dec 31, 2019. Data on deaths came from the national registry of Births, Deaths and Marriages. Cases were excluded if location or date of death were not recorded or if the person was a non-resident. Daily maximum and minimum temperature were measured and recorded by the Bureau of Meteorology. Hot weather was defined as mean temperature greater than 35°C over a 3-day lag. Socioeconomic status as indicated by Index of Relative Socioeconomic Disadvantage was mapped from location at death.

Findings During the study period, 34 782 deaths were recorded; after exclusions 31 800 deaths were included in statistical analysis (15 801 Aboriginal and 15 999 non-Indigenous). There was no apparent reduction in heat susceptibility despite infrastructural and technological improvements for the majority non-Indigenous population over the study period with no heat-associated mortality in the first two decades (1980–99; relative risk 1·00 [95% CI 0·87–1·15]) compared with the second two decades (2000–19; 1·14 [1·01–1·29]). Despite marked socioeconomic inequity, Aboriginal people are not more susceptible to heat mortality (1·05, [0·95–1·18]) than non-Indigenous people (1·18 [1·06–1·29]).

Interpretation It is widely believed that technological and infrastructural adaptations are crucial in preparing for hotter climates; however, this study suggests that social and cultural adaptations to increasing hot weather are potentially powerful mechanisms for protecting human health. Although cool shelters are essential during extreme heat, research is required to determine whether excessive exposure to air-conditioned spaces might impair physiological acclimatisation to the prevailing environment. Understanding sociocultural practices from past and ancient societies provides insight into non-technological adaptation opportunities that are protective of health.

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Introduction

Without adaptation, climate change is projected to increase heat-associated mortality globally with disproportionate outcomes in hotter peri-equatorial and poorer countries.[1] The way that health will be affected by increasing environmental heat is complex with adaptive biophysiological (acclimatisation), sociocultural, and infrastructural or technological factors potentially attenuating outcomes.[2–4] There is little evidence to guide which of these factors are most effective in mitigating adverse health impacts. However, the globally predominant real-world response is currently focused on improving infrastructure, air-conditioned spaces, and public health system responses to heat.[5–7]

Climate adaptation can be autonomous and naturally occurring with population heat-mortality characteristics showing acclimatisation across the latitudes.[8] Throughout time, societies have developed social and

Research in context

Evidence before this study

We searched PubMed using the terms "heat", "mortality", and "adaptation", for articles published in English from Jan 1, 2000, up until Feb 1, 2022. Extreme environmental heat leads to heat-related illness and increased population mortality. Potential mechanisms to reduce such harms include technological, infrastructural, and sociocultural adaptations. There is evidence that infrastructural and technological measures such as air-conditioning and access to cool space during extreme heat events can be protective of health. There are many long-standing sociocultural heat-avoidant practices around the world that have not been evaluated and are potentially powerful means of protecting human health.

Added value of this study

Sociocultural practices that reduce exposure to heat such as reducing physical exertion in hotter parts of the day might be protective, emphasising the importance of listening to and understanding First Nations knowledges of living with heat. While air-conditioning might provide safe shelter from extreme heat events, if used in ways that prevent human physiological acclimatisation to very hot climates air-conditioning might increase vulnerability to heat.

Implications of all the available evidence

There is a deficit of acknowledgment and implementation of sociocultural practices that are protective against environmental heat. Although cool refuge is essential during extreme heat events, further research is required to determine if prolonged time in air-conditioned spaces in hot climates might be harmful to health.

cultural practices to deal with environmental heat, such as the siesta which is thought to have evolved in regions where heat adversely affected capacity for physical work during the middle of the day.[9] Similarly Northern Australian Aboriginal communities listen and watch for environmental cues and respond accordingly if they know hot weather is on its way. There is very little research evaluating such sociocultural adaptations to heat and similarly almost no attention given to the potential for such practices to protect communities from extreme heat.

> "Wumpurrarni [Warumungu Aboriginal people] know there's going to be a big drought when we see all the lizards out sitting on top of the rocks and on top of the ant hills, that's just noticing that there's drought coming, there's a really hot season on the way. For a hot day, he'll tell you early in the morning, before the sunrise, you can see that sky, it'll tell you it'll be a very hot day today. So you've got to be prepared. All the birds will be singing out in the morning letting you know that it's going to be a very hot day today. A long drought will tell you about animals, not coming out or they all locked away because there is going to be a big drought…And when it comes, hot weather or a big drought, people would go to a permanent water hole that always holds water. They'll go stay near the best water, the soak, so they're going to have water right through the season, right through the hot season."
>
> *NFJ*

Although technological responses such as air-conditioning increase human comfort there is conflicting evidence of relative health benefits for various options. There is evidence that air-conditioning protects population health and plays a crucial role in human heat adaptation particularly during heatwaves where vulnerable populations might not be able to shelter from extreme temperatures.[2,10,11] However, the optimal relationship between cooling technologies and population health, physiological adaptation, thermal comfort, and safety is not well understood. For instance, a study comparing people who worked in naturally ventilated versus air-conditioned buildings showed greater physiological heat adaptation in those from naturally ventilated buildings.[12] There is emerging research addressing this knowledge deficit with a 2021 study using biophysical models showing a global role in both affordable access to and health benefits from fans as adaptive technology to hot weather despite the prevailing opinion that fans offer little protection.[13]

The climate of the Northern Territory of Australia is defined by very hot temperatures with the northern tropical Top End region experiencing hot and humid conditions year-round, and the climate of the arid Centre region characterised as very hot and dry with short but nocturnally cold winters.[14]

The Northern Territory has the highest proportion of Aboriginal and Torres Strait Islander people of any state of Australia (30% compared with 3% nationally[15]) with vast remote areas where 65 Aboriginal Nations retain ancient and strong traditional language and culture.[16] These communities are harmonious with the climate and environment and there is a deep knowledge of how to survive and thrive in hot weather. From an infrastructural and technological point of view, however, these communities have not benefited from the same material progress experienced throughout the rest of Australia. There remains extreme inequity for Aboriginal people in the Northern Territory[17] manifesting for instance in the highest rates of homelessness in the nation at over 12 times the national average,[18] extreme energy insecurity, overcrowded and extremely poor-quality housing,[19,20] very poor health outcomes, and low life expectancy.[21]

> "Today we still live like we used to live in humpies [make-shift structures without insulation or other basic housing standards including running water or electricity], because our houses are poor and overcrowded...So now we live in houses that are not luxury, you know, not very good. I think these houses have been built for England or somewhere, cold country. We need houses to be built for this weather that are made for this climate here today."
>
> *NFJ*

In contrast, the non-Indigenous population of the Northern Territory has experienced similar prosperity as the rest of Australia over the past four decades. As an example of the real socioeconomic gains, it is estimated that air-conditioning penetrance increased from 52% in 1980 to 93% in 2010.[22] These numbers do not include air-conditioning ownership for Aboriginal people, most of whom live in social housing where government policy mandates households in the hottest parts have ceiling fans and not air-conditioners.[19]

The effects of extreme heat in the Northern Territory provide an opportunity to understand how social and cultural background can either protect or expose people to risk of adverse outcomes. In this study we aim to examine the association of 40 years of mortality and climatic data in a hot region with a distinctively polarised population to understand and evaluate infrastructural, technological, and sociocultural adaptive practices of living with extreme heat.

Methods

Research approach

In this case time series, we matched temperature at the time of death using a modified distributed lag non-linear model for all deaths in the Northern Territory, Australia, over a 40-year period. Ethics approval was granted through the Northern Territory Department of Health Human Research Ethics Committee (2019-3544). This research takes a respectful, reciprocal, and relational approach with the analysis and interpretation grounded in Warumungu knowledge that has emanated from continuous deep connections to Country (traditional lands of Warumungu people) and culture over millennia. The quantitative findings were discussed with Norman Frank Jupurrurla (NFJ) who provided his story behind the Warumungu peoples' deep understanding of Country, how they sensed and responded to environmental cues to sustain their wellbeing during extreme weather including heat and drought. NFJ's interpretation is presented verbatim to provide a sociological layer to the analysis, giving voice to those whose health has been severely compromised by colonisation yet remain remarkably strong due to culture and valuable knowledge of Country.

> "Wumpurrarni [Aboriginal people] pass their knowledge down from generation to generation, but they keep carrying their knowledge and they practice their knowledge every day. A lot of things they practice – their language, their lifestyle, and how they live... A Mukunjungku is someone with lot of ideas about the ways of living, he's got a different style and he's a powerful man as well, a man with a lot of knowledge of the spirit of this country and land. Our country means a lot to us, more than anything, and the country tells us many things. The country, the Manu – the plants, the trees and the animals – tell us what season it is, what we have to do, and what's coming, what's going. The Manu tells us before the flood, the animals will tell us what's coming. So that's like a reminder, wake you up, you know, look – there's a wet season coming or a big summer, a big drought. The Manu will tell us before the drought has come. So that's just country."
>
> *NFJ*

Mortality data

We assessed the data for all deaths in the Northern Territory as recorded by the national registry of Births, Deaths and Marriages (BDM) for a 40-year period from Jan 1, 1980, to Dec 31, 2019. BDM data include date, age, and location of death; residential address; sex; Indigenous status; and cause of death recorded as the text written on the death certificate.

Cases excluded from further analysis were those whereby either location or date of death were not recorded or unknown. Non-resident (visitor) deaths were also excluded as these would bias results given the large tourism industry and seasonal labour force that predominantly operates in the cooler periods of the year between May and August.

Location in the period before death was defined as location of death on the death certificate. In a case whereby the death certificate did not record the location of death and only the residential address, or when the location of death was recorded as within a hospital we coded the location of death as the residential address. For hospital deaths it was assumed that the triggering event for hospitalisation and subsequent death occurred within the community.

Climate

Over the past century most of the landmass of the Northern Territory climate progressively warmed. In the past 40 years there was a relatively small region that experienced cooling (figure 1), although this pattern has reversed in the past decade.

The climate of the Northern Territory is defined by two predominant zones—humid and arid. Taking Darwin as representative of the Tropical Top End region of the Northern Territory the daily temperature over the study period was very high and within a limited seasonal range (mean 32·2°C [SD 1·7]) with warm overnight minimums (mean 22·8°C [3·1]). Using Alice Springs as representative of the Central arid zone there was much greater seasonal variability with very hot summers and mild winters (mean daily maximum 29·1°C [7·4] and mean overnight minimum 13·2°C [7·6]).

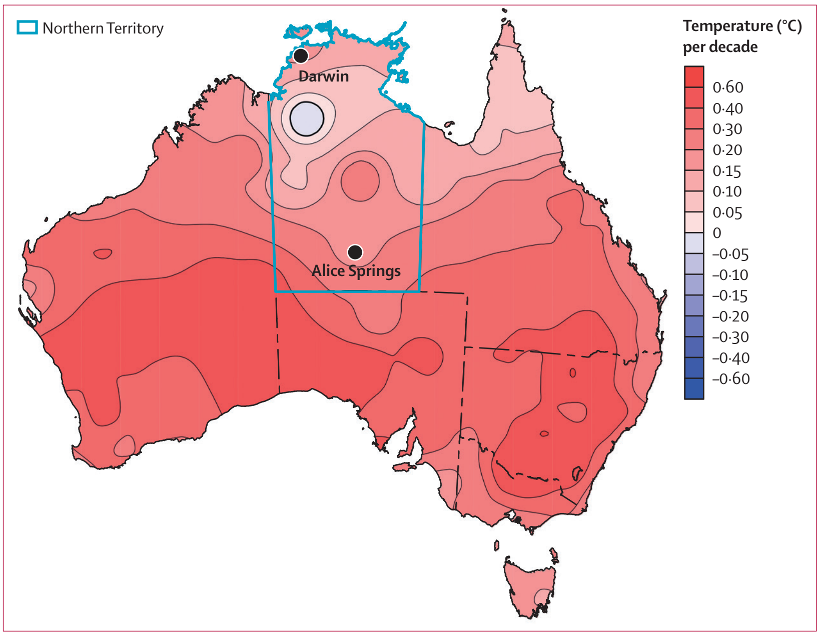

Figure 1: **Temperature trends across Australia, 1980–2019**

Climate variables for the Northern Territory including daily maximum and minimum temperature were measured and recorded by the Bureau of Meteorology with data recorded at individual observation stations across Australia since 1910 through the Australian Climate Observations Network–Surface Air Temperature.[23] The Scientific Information for Land Owners (SILO) database[24] uses the Bureau of Meteorology raw observational data that is then spatially interpolated to create a gridded raster of estimated climate variables on a 1 km² grid across Australia. We used SILO data to obtain temperature records for each of the 163 Northern Territory locations that BDM data listed as location of death on the day of death. Climate zone at death was defined according to the Australian Building Codes Board Northern Territory Climate Zone map, with humid zone north of a longitudinal line approximately equidistant between Darwin and Alice Springs (figure 1) and arid zone to the south of this line.[25]

Study population

The Northern Territory is one of the most sparsely populated landmasses in the world. In 1980 the population of the Northern Territory was estimated at 121 000, of whom approximately 38 000 were Aboriginal.[26] In 2020 the population had grown to 246 000 with 75 000 being Aboriginal. There is one small city, Greater Darwin, with a population in 2020 of 147 000 in the Top End region, and Alice Springs being the second largest centre (population 25 000) in the Centre region.

To show the extent of socioeconomic inequity between broader Aboriginal and non-Indigenous communities in the Northern Territory over the study period and continuing today we used Australian Bureau of Statistics census data. The Socio-Economic Indexes for Areas ranks areas of Australia by percentile based on relative socioeconomic status.[27] We used the Index of Relative Socioeconomic Disadvantage (IRSD) for each death (as located by suburb where the death occurred) by national ranking. To show the extent of this confounding socioeconomic inequity and the substantial differences in technological and infrastructural capacity to shelter from heat between groups a Mann Whitney U test was conducted between Aboriginal and non-Indigenous IRSD.

> "Papulanyi [non-Indigenous people] have got a better way of living here [in remote Northern Territory], I tell you that, that's for sure. They live in luxury, they're rich. They've got air conditioners, they've got lawns, they've got big trees around their houses. But us Wumpurrarni [Warumungu Aboriginal people], we just live day by day, day by day. The government just throws us in old houses, just give us a key and say this is your house, but it's not the way we want our house to be, how we want to live and what kind of house we want."
>
> *NFJ*

Statistical modelling

Population health impacts of environmental exposures are modelled using regression analyses.[28] In this study, temperature-associated mortality analysis was conducted using the case time series method applied to small-area data to examine excess mortality above baseline that is attributable to temperature exposure.[29] Our analysis and interpretation focused solely on heat-associated mortality and did not explore cold-associated mortality as the study objective was to understand heat-associated mortality in a hot climate. The case time series method is based on the definition of multiple time series for each unit allowing associations of outcomes (such as death) with time-varying risk exposures (such as ambient temperature) to be calculated in a manner that controls for both longitudinal and case level confounders in observational data including seasonality.[30] The case time series method offers a way to perform analyses at individual or small-area level while applying the advanced time series technique, distributed lag non-linear method, to model the effect of risk of exposure over a set of time periods (lags). We chose this method over time series and other regression models due to the smaller and widely dispersed population in the Northern Territory with many of the 163 locations recording limited number of deaths.[1,3,7,8,28,29]

We first created mortality time series for each of the 163 locations where a death was recorded and matched with related temperature series. We fit a quasi-Poisson conditional Poisson regression model stratified by Northern Territory location, year, and month, therefore allowing a differential baseline mortality and trends across the different geographical areas to account for distinct baselines and trends in climate, population, and seasonality. Our outcome measure was counts of deaths and we used a lag of 3 days for all analyses as our study focused on heat, which has a brief effect of days.[31] The model was fit separately for Aboriginal and non-Indigenous subgroups. Hot weather was defined as mean of the 3-day lag period greater than or equal to 35°C.[32]

We ran this analysis on the total population for the 40-year study period examining differences in patterns based on Aboriginal status and location. Given the improvements over time in socioeconomic status and air-conditioning penetration for non-Indigenous people compared to the lack of such improvements for Aboriginal people we examined the first two-decade period (1980–99) and compared this to the second two-decade period (2000–19). Two twenty-year periods were used instead of four decade-long periods on the basis of statistical power in a relatively small population.

As age is a known risk for heat-associated mortality[33] we assessed temperature-associated mortality for younger and older age at death. Given that median age at death was 59 years (IQR 32; 65 years [28] for non-Indigenous and 52 years [31] for Aboriginal people), older age was defined as older than 50 years.

The results of the estimation are shown as curves of the overall cumulative relative risk of mortality associated with mean ambient temperature. Temperature-associated mortality rates are expressed as relative risk (RR) with 95% CI against 3-day lag mean temperature.

Role of the funding source

There was no funding source for this study.

Results

Between Jan 1, 1980, and Dec 31, 2019, 34 782 deaths were recorded in the Northern Territory. We excluded 1284 deaths with missing location or date of death and 1698 non-resident deaths, leaving 31 800 deaths for analysis. Of these deaths, 13 428 deaths occurred in the first two decades (1980–99) and 18 372 in the latter two decades (2000–19). There were 15 999 non-Indigenous deaths and 15 801 Aboriginal deaths (table).

In the first decade (Jan 1, 1980, to Dec 31, 1989) the mean age at death was 51·8 years (SD 23·4) for non-Indigenous and 51·7 years (SD 20·4) for Aboriginal people after excluding infant deaths (appendix). In the fourth decade (Jan 1, 2010, to Dec 31, 2019) the mean age at death for Aboriginal people was 53·2 years (SD 18·5; a gain of 1·45 years) and for non-Indigenous people it rose to 66·9 years (SD 17·8; a gain of 15·2 years).

The IRSD at location of death between Aboriginal and non-Indigenous people in this cohort was pronounced, with a mean national ranking by suburb at death of 27% (SD 30·4) for Aboriginal people and 67% (28·3) for non-Indigenous people (p<0·0001; appendix). This finding underestimates the true extent of the social inequity—for instance, there were 2066 Aboriginal deaths in the 80th percentile IRSD (compared with 8893 non-Indigenous deaths) and 3816 deaths in the 40th percentile (compared with 2438 non-Indigenous deaths). These two peaks in Aboriginal deaths represent deaths in Darwin (85% IRSD national ranking) and Alice Springs (31% IRSD national ranking), respectively. For both these urban centres the majority of Aboriginal people reside in Town Camps (Community Living Areas) in settler-colonial imposed conditions of extreme poverty.[34] 39% (6171) of Aboriginal people in the study lived in locations ranked in the bottom 1% of IRSD suburbs in Australia compared with 1% (266) of non-Indigenous people; the majority of these non-Indigenous people would have been employed in high-paying remote community service positions.

	Aboriginal (n=15 801)	Non-Indigenous (n=15 999)	Total (n=31 800)
Time period			
1980–99	6995 (44%)	6433 (40%)	13 428 (42%)
2000–19	8806 (56%)	9566 (60%)	18 372 (58%)
Climate zones			
Humid	10 064 (64%)	13 134 (82%)	23 198 (73%)
Arid	5737 (36%)	2865 (18%)	8602 (27%)
Age			
<50 years	7220 (46%)	4042 (25%)	11 262 (35%)
≥50 years	8581 (54%)	11 957 (75%)	20 538 (65%)
Location			
Urban	1957 (12%)	8404 (53%)	10 361 (33%)
Rural	5731 (36%)	6362 (40%)	12 093 (38%)
Remote	8113 (51%)	1233 (8%)	9346 (29%)

Data are n (%).

Table: **Deaths by time period, climate zone, age group, and location**

Over the 40-year period there was no statistically significant heat-associated mortality in the total population (appendix). The sample size for deaths in very hot weather was small leading to wide confidence intervals.

Aboriginal populations did not have significant heat-associated mortality (RR 1·05 [95% CI 0·95–1·18]) but non-Indigenous populations did (1·18 [1·06–1·29]). Confidence intervals between these two groups are overlapping (figure 2).

See Online for appendix

There was no heat-associated mortality from 1980 to 1999 (RR 1·00 [95% CI 0·87–1·15]) but there was from 2000 to 2019 (1·14 [1·01–1·19]), although the confidence intervals of the two time periods are overlapping (figure 3; appendix). Comparing total deaths over the 40-year period, deaths in the second 20-year period appear to have driven the overall trend towards heat-associated deaths for all deaths over the 40-year period (figure 3).

Heat-associated deaths were higher in the humid zone (RR 1·24 [95% CI 1·05–1·45]) compared to the arid zone (1·13 [1·01–1·27]); however, the confidence intervals were overlapping (figure 4; appendix).

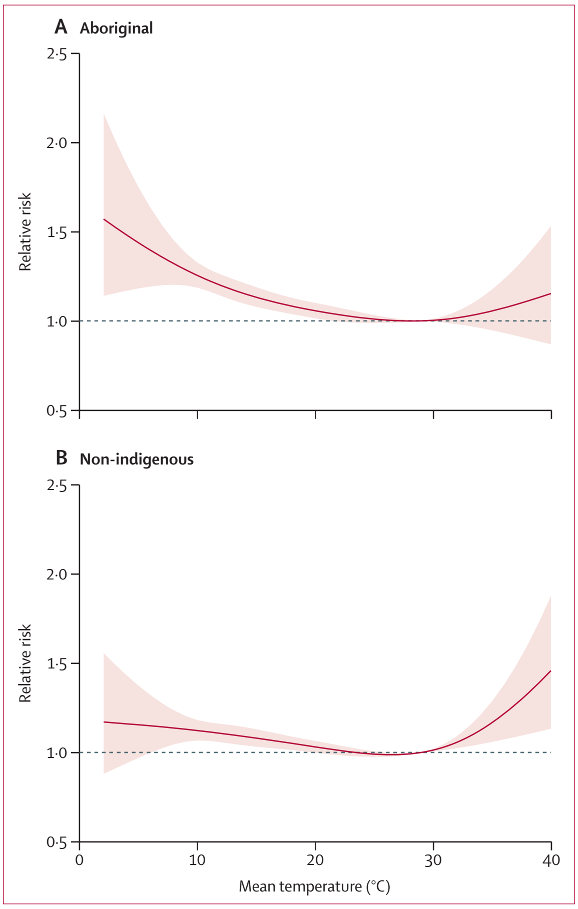

Figure 2: **Relative risk for temperature associated deaths by mean temperature (3-day lag) for Aboriginal (A) and non-Indigenous (B) people, 1980–2019**
Red shading indicates 95% CI.

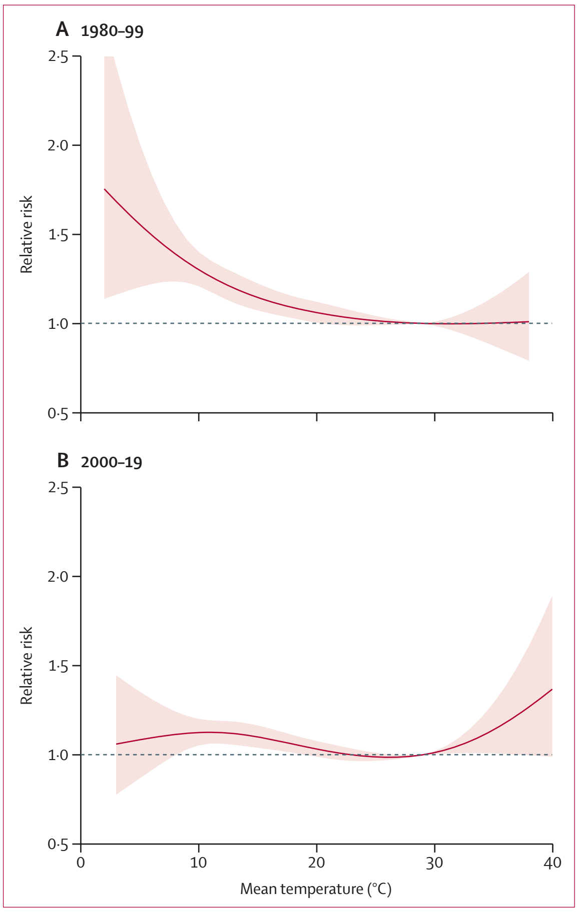

Figure 3: **Total deaths by mean temperature (3-day lag) from 1980 to 1999 (A) and from 2000 to 2019 (B)**
Red shading indicates 95% CI.

For people younger than 50 years there was no temperature-associated mortality (RR 1·07 [95% CI 0·94–1·23]). There was a significant association for people aged 50 years and older for heat-associated mortality (1·19 [1·08–1·33]; figure 5; appendix).

Reflections on the findings of this study by NJF are in the panel.

Discussion

The principal findings of this study are that there has been no evident improvement in heat-associated mortality for non-Indigenous people over a 40-year period despite substantial socioeconomic and infrastructural gains that have led to longer lives. Despite the profound inequity in housing and socioeconomic status and resultant severely impaired access to cooling technologies such as air-conditioned space, Aboriginal people living in the same hot climate do not have higher heat-associated mortality than non-Indigenous people.[35]

For non-Indigenous people in the Northern Territory, sociocultural norms are of European origin: employment practices that see outdoor workers exposed to the hottest parts of the day, a lack of awareness or acceptance that physical exercise in hot weather can be dangerous, high levels of exposure to potentially maladaptive indoor air-conditioned time that might promote sedentary lifestyle and dampen short-term physiological adaption to hot weather, Eurocentric building infrastructure designed to be air-conditioned rather than passively cooled, and a myriad of other subtle behaviours and practices that often appear to be at odds with the local climate rather than to accept and live within its constraints.[36]

It can be hypothesised that one of the reasons that Aboriginal people do not have substantially higher rates of heat-associated mortality in the context of extreme socioeconomic inequity is that they have a number of non-material protective factors that are difficult to disentangle. Firstly Aboriginal people have resided in a hot climate for thousands of generations and this extended inter-generational geographical tenure has been formative of sociocultural practices that are synchronistic with and presumably protective against adverse weather conditions and other ecologically related health risks.[37] This many generational climatic and

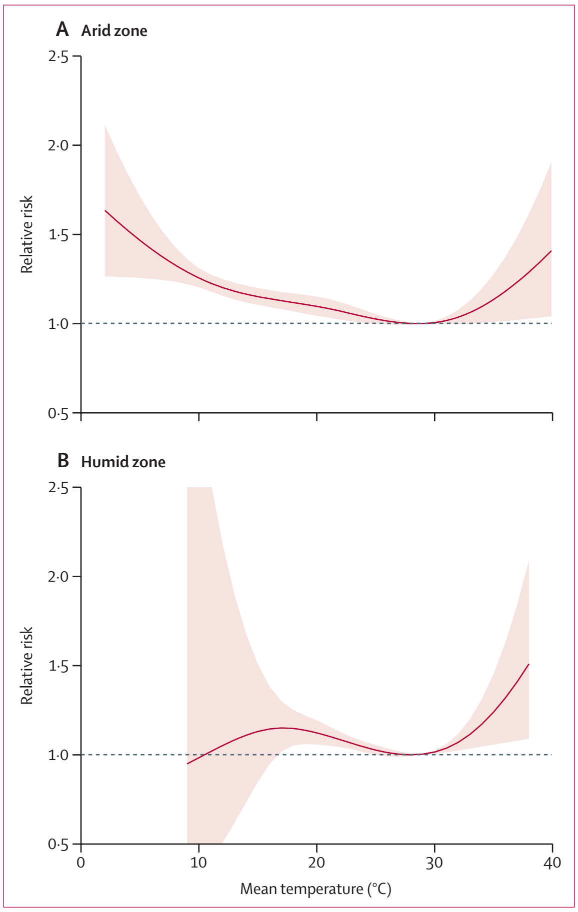

Figure 4: **Deaths by mean temperature (3-day lag) in arid (A) and humid (B) zones**
Red shading indicates 95% CI.

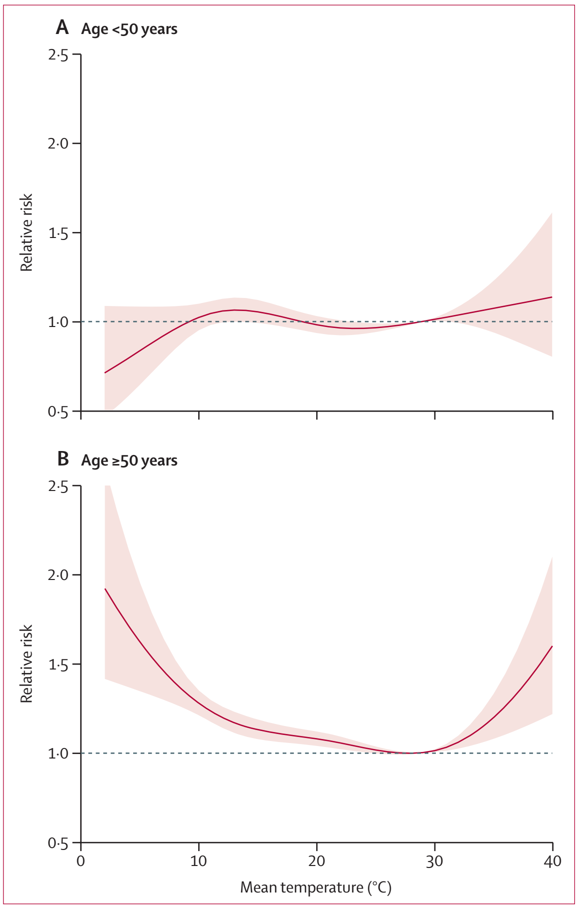

Figure 5: **Deaths by mean temperature (3-day lag) in people younger than 50 years (A) and aged 50 years and older (B)**
Red shading indicates 95% CI.

ancestral history might provide a degree of genetic advantage during periods of hot weather.[38]

Climate is theorised to have been a major factor shaping societal culture, which can be defined as a rich complex of values and practices passed on and changed from generation to generation.[39] Given that Indigenous cultures developed within the constraints of climate and environment of ancestral lands and in some cases across climatic ages, there is an increasing awareness that Indigenous societies and their contemporary responses to and understanding of climate change provide important insights into climate adaptation.[40,41] The relevance of shifts in such societal culture in high-income and non-Indigenous societies can be seen for instance in the siesta, a brief daytime sleep. The siesta which has its roots in agrarian 17th century society has essentially disappeared as a European cultural entity as a result of global economic pressures and its potential benefits have subsequently been lost.[42,43]

There are also more immediate processes that might result in lower heat-associated mortality for Aboriginal people in the Northern Territory. Given the substantially lower economic and infrastructural resources available to Aboriginal people they are likely to spend greater periods of uninterrupted time in hot weather outside of air-conditioned space. Such conditions are conducive to shorter term physiological acclimatisation responses that are known to improve heat tolerance.[44] Many non-Indigenous people spend a substantial amount of sedentary time in air-conditioned spaces and are potentially less likely to benefit from short-term physiological adaptations that environmental heat exposure naturally induces.[12]

While noting that prolonged heat exposure leads to physiological acclimatisation within the bounds of heat tolerance, excessive heat exposure beyond these limits manifests as heat-related illness. Recent heat events between 2018 and 2021 in the Northern Territory have been unprecedented in their severity and duration with more severe extreme heat on its way and temperatures are already approaching limits of human physiology.[45] There is a cascading effect of extreme heat on wellbeing that is amplified by low socioeconomic status; for instance energy insecurity is exacerbated by hot weather as a result of high air-conditioning requirements in poorly insulated and overcrowded dwellings, compromising electricity supply and refrigeration along with other essential health hardware and storage of medicines, which in turn worsens food security, amplifying heat-susceptible physical and mental illnesses,[19,46] impairing educational attainment,[47] and worsening social cohesion.[48] Despite the apparent advantages that Aboriginal people have had in regard to heat-associated mortality over the period of this study there is an urgent need to address the severe socioeconomic and infrastructural circumstances that define these communities to better prepare for future climate scenarios.

There are opportunities to learn how best to adapt to a warming environment through a nuanced understanding of fundamental differences in social, cultural and behavioural practices between Aboriginal and non-Indigenous people. For Aboriginal people with multigenerational deep spatial knowledges based on a worldview of culture and environment,[49] these are lifestyle and cultural practices developed over many generations that are harmonious with and conscious of the environment: seasonal knowledge and timing of social and cultural practices, exertion avoidance in extreme heat, outdoor sleeping practices capitalising on prevailing wind, evening and nocturnal social activity in hot seasons and daytime activity in cold, and a fundamental resistance to accepting non-Indigenous values of capitalism as core to societal culture.

There are several limitations of this study. Firstly, there were low numbers of deaths, limiting power and subgroup analysis. Lag for cold-associated mortality extends to 3 weeks or more and in our analyses we only examined 3-day lag effect; however, the explicit objective of our study was to examine heat-associated mortality. Similarly, there is a complex relationship between heat, humidity and health.[36] Given the strong correlation between heat and humidity we elected to focus on heat alone and have not excluded a humidity effect on mortality. There are many potential confounders of heat-associated mortality over the study period including generational lifespans, improvements in health-care capacity, complex relationships between housing, socioeconomic disparity, and culture, and the evolving impacts of colonisation on Aboriginal people in the Northern Territory. The interplay between these confounders cannot be further elucidated by this analysis.

From this hypothsis-generating study, it can be broadly concluded that physiological and sociocultural adaptations are potentially powerful mechanisms in preparing for future warming scenarios. Such social and cultural knowledge is held by various communities around the globe. There is potential to learn lessons that are not biomedical in construct and that are of high health value.

In particular, these findings are important for housing policy and design in very hot regions of the world. It is clear that cool (and thus air-conditioned) spaces are essential refuge during extreme temperatures including heatwaves, but it is also possible that extended periods in air-conditioned spaces might be physiologically maladaptive to the prevailing climate, particularly in very

Panel: Reflections on the findings of this study by Norman Jupurrurla Frank (Warumungu Elder)

"Our culture is as old as this country, it is very old. And how we live now, it's changing, but our culture comes from the old ways. In the old days, in the wintertime, people would walk out in the desert, collecting seeds and bush potato in the desert when it was cool. In summertime they would live in the river and creek country, near the water. In the very hot weather they'd be around the spring country where they could get water. They used their gwarda back then, using their kumpumpu. They wouldn't go into the desert when it was very hot, too dangerous. Those old people, they were Mukunjungku.

Gwarda means thinking, listening, hearing, seeing, concentrating, feeling what is happening around you. Us Wumpurrarni [First Nations Warumungu people], we have gwarda for that hot weather and what it can do to you. In Warlpiri [First Nations to west of Warumungu homelands], the word is Launga. In Alyawarra [First Nations to the east] they say Ilbpa. All First Nations people in Central Australia have a word for gwarda. You'll be sitting down under a rockhole or a shady tree, and a cold breeze will come across, and you can understand things around you – the country will tell you what is happening. The birds will tell you signs. Dogs also, they'll walk alongside you and he'll tell you something is wrong. Dogs have more gwarda than people. Dogs will tell you something is wrong before you even notice.

Gwarda shapes your kumpumpu, your brains. Mukunjungku, this is a person, a wise person, a person with a lot of knowledge that comes from gwarda and shapes the kumpumpu. Mukunjungku is someone who learns from their experience, figuring it out.

Pupulinji [non-Indigenous people], they got no gwarda, they aren't listening, they aren't thinking – they are just thinking about payday and getting the job done. He's not thinking about his ngattu, his body, and what he's doing to it in that really hot weather. Their whole culture is around work and money. They got to do what their boss says, if they don't do it they don't get paid and the job doesn't get done.

Money makes Pupulinji move and talk.

But for Wumpurrarni people though, it was the weather, the reptiles, birds and other animals. In wintertime, everything is locked away, it is too cold – snakes, lizards, anything. But summertime they are all out, that's the best time for ceremony because there is plenty more food around. Instead of carrying a fridge around all day, in the old days they could catch fresh food every day. It was the environment, the seasons, ceremony and culture that made us move and talk."

hot regions. The focus of housing in hot climates should be to ensure passive cooling design where occupants live comfortably within the predominant climate and at the same time requiring minimal energy costs for cooling. The use of air-conditioned space should ensure safe retreats during extreme heat events, but should be limited in intensity to reduce energy consumption and improve human physiological acclimatisation. However, over use of air-conditioning to induce thermal comfort might undermine behavioural and physiological mechanisms protective of health. Further research is required to better understand the optimal relationship between passive cooling, air-conditioning, thermally safe retreats, and optimal conditions for human physiological acclimatisation

Reflecting on the constant political pressure to remove the siesta in Spain on the basis of improving economic productivity,[50] a clear example can be seen where the entirety of cultural value is placed upon a healthy economy, rather than healthy planet and population. Perhaps the most important tool we have to combat climate change is culture change, and as a global society, we need to learn how to embrace cultural change in many dimensions. For planetary health, First Nations scholars emphasise the need to reject colonial and capitalist ideologies and return to Indigenous epistemologies that emphasise the importance of respectful relationships with Country and the natural environment.[51]

Contributors

SQ collated the data and performed statistical analysis, contributed to interpretation and write up of the manuscript, and undertook interviews and transcriptions with NFJ and VM. AL performed statistical analysis and contributed to interpretation and write up of the manuscript. VM provided cultural oversight of academic work and contributed to the write up and revisions of the manuscript. PH provided review of meteorological data and contributed to the write up of the manuscript. MB provided review and interpretation of results. AG provided oversight of statistical analysis. KLE provided interpretation of results, oversight of write up of the manuscript, and oversight of revisions. NFJ provided foundational concepts of the research and social and cultural interpretation of results. SQ, AL, and PH directly accessed and verified the underlying data reported in the manuscript. All authors had full access to the data and held final responsibility for the decision to submit for publication.

Declaration of interests

AG received funding from Medical Research Council UK. PH received funding from the Australian Government's National Environmental Science Program. MB is the Managing Director of Thermal Hyperformance. All other authors declare no competing interests.

Data sharing

Mortality data included in this study were from the Northern Territory registry of Births Deaths and Marriages (agd.registrargeneral@nt.gov.au). Mortality data included date of death, age at death, location of death, residential address at time of death, and Indigenous status. The mortality data contains sensitive identifiable information and access to this data requires ethics approval through the Human Research and Ethics Committee of Northern Territory Health (https://health.nt.gov.au/data-and-research/nt-health-research/research-ethics). Climate variables were collected by the Australian Bureau of Meteorology (https://www.longpaddock.qld.gov.au/silo/gridded-data/). Climate variables included date of temperature, and maximum and minimum temperature on that date. Socioeconomic Index for Areas data were from the Australian Bureau of Statistics (https://www.abs.gov.au/websitedbs/censushome.nsf/home/seifa), and included Index of Relative Socioeconomic Disadvantage for each location.

Editorial note: The Lancet Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

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