The burden of occupational injury attributable to high temperatures in Australia, 2014–19: a retrospective observational study

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The known: High temperatures are associated with increased risk of occupational injury, but the proportion of this burden that is attributable to high temperatures has not been assessed in Australia.

The new: Using the comparative risk assessment approach, we estimated that 2.3% of the national occupational injury burden, assessed as disability-adjusted life years (DALYs), was attributable to high temperatures. The proportion was largest in tropical regions (3.5%), and in New South Wales and Queensland (2.9%).

The implications: High temperatures increase the risk of workplace injury. Preventive measures tailored to local climatic and working conditions will be required to contain the heat-attributable burden of disease as temperatures rise further in Australia.

Abstract

Objectives: To assess the population health impact of high temperatures on workplace health and safety by estimating the burden of heat-attributable occupational injury in Australia.

Study design, setting: Retrospective observational study; estimation of burden of occupational injury in Australia attributable to high temperatures during 2014–19, based on Safe Work Australia (work-related traumatic injury fatalities and workers' compensation databases) and Australian Institute of Health and Welfare data (Australian Burden of Disease Study and National Hospital Morbidity databases), and a meta-analysis of climate zone-specific risk data.

Main outcome measure: Burden of heat-attributable occupational injuries as disability-adjusted life years (DALYs), comprising the numbers of years of life lived with disability (YLDs) and years of life lost (YLLs), nationally, by Köppen–Geiger climate zone, and by state and territory.

Results: During 2014–19, an estimated 42 884 years of healthy life were lost to occupational injury, comprising 39 485 YLLs (92.1%) and 3399 YLDs (7.9%), at a rate of 0.80 DALYs per 1000 workers per year. A total of 967 occupational injury-related DALYs were attributable to heat (2.3% of occupational injury-related DALYs), comprising 890 YLLs (92%) and 77 YLDs (8%). By climate zone, the heat-attributable proportion was largest in the tropical Am (12 DALYs; 3.5%) and Aw zones (34 DALYs; 3.5%); by state and territory, the proportion was largest in New South Wales and Queensland (each 2.9%), which also included the largest numbers of heat-attributable occupational injury-related DALYs (NSW: 379 DALYs, 39% of national total; Queensland: 308 DALYs; 32%).

Conclusion: An estimated 2.3% of the occupational injury burden in Australia is attributable to high ambient temperatures. To prevent this burden increasing with global warming, adaptive measures and industry-based policies are needed to safeguard workplace health and safety, particularly in heat-exposed industries, such as agriculture, transport, and construction.

In our earlier investigations of the influence of ambient temperature on health and safety in the workplace, we found that heat stress can lead to specific illnesses, such as heat exhaustion and heat stroke, and increase the risk of a diverse range of occupational injuries, including being struck by moving objects, mental stress, fractures, burns, wounds, and lacerations.[1-4] These injuries are often mediated by factors such as dehydration, fatigue, and impaired cognitive and physical function.[1,5] Workers in certain industries, including agriculture, mining, transportation, manufacturing, and construction, are at particular risk of heat-related injuries.[1,2]

In 2020, economic productivity was reduced in many countries, not only by pandemic-related lockdowns, but also by extreme heat.[6] The ramifications of these losses and heat-related injuries extended beyond workers and employers to the broader community and economy. Further, heat-related illnesses and injuries can cause financial, mental, and social problems for both individuals and health care systems; for example, the estimated annual cost of treatment and rehabilitation for people with heat-related injuries in Spain during 1994–2013 was €28.1 million.[7]

Although occupational exposures and hazards have been investigated as risk factors for injury and adverse health outcomes both globally[8] and in Australia,[9] the proportion of the occupational injury-related burden of disease attributable to high temperatures has not been quantified in Australia. We therefore assessed the long term consequences of occupational injuries, both in terms of years of life lost because of premature deaths and of years lived with illness or injury, and used Australian Institute of Health and Welfare (AIHW) methodology to estimate the heat-attributable occupational injury burden in Australia by Köppen–Geiger climate zone,[10] and by state and territory. Our aim was to provide information that can inform local decision making regarding workplace safety as global temperatures rise.

Methods

In our retrospective observational study, we analysed AIHW national, state, and territory burden of disease data for occupational injuries during 1 July 2014 – 30 June 2019 to estimate the occupational injury burden of disease as disability-adjusted life years (DALYs), comprising years of life lived with disability (YLDs) and years of life lost (YLLs).

The number of YLLs was calculated by multiplying the number of occupational injury deaths, as recorded in the Safe Work Australia work-related traumatic injury fatalities database,[11] by life expectancy at the age of death, as estimated by the AIHW Australian Burden of Disease Study.[9] Following standard AIHW procedure, we combined and adjusted data from two databases

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to estimate the number of YLDs associated with occupational injuries in Australia: the Safe Work Australia national dataset for compensation-based statistics[12] and the AIHW National Hospital Morbidity Database[13] (further details: Supporting Information).[9] The number of occupational injury-related DALYs was calculated by summing the numbers of YLDs and YLLs.

We report the effects of high temperatures nationally and for each of the twelve Köppen–Geiger climate zones in Australia: tropical (Af, Am, Aw), arid (BSh, BSk, BWh, BWk), and temperate or Mediterranean climate zones (Cfa, Cfb, Csa, Csb, Cwa) (Box 1).[10] We calculated the mean, median, and modal daily temperatures for each climate zone from temperature data in the Scientific Information for Land Owners (SILO) dataset[14,15] for the centroid of each Statistical Area Level 2 (SA2) within a climate zone. SA2s include a mean of 10 000 residents.[16]

The number of employed people in each climate zone and state or territory was derived from 2016 Australian Bureau of Statistics national census SA2-level labour force data (using Census TableBuilder),[17] and the proportions of the national total calculated. Population-adjusted YLDs and YLLs for occupational injury in each climate zone and state or territory were calculated by multiplying the labour force proportion by the national burden of disease, and expressed as number of injuries per 1000 employed people.

Burden of occupational injury attributable to high temperatures

We calculated the heat-attributable burden of occupational injury — the proportion of the total burden attributable to heat exposure — using our previously described methodological framework.[18] "Heat" was defined as a temperature exceeding that at which the health risk is zero; that is, the theoretical minimum risk exposure distribution (TMRED). The heat-attributable burden is equivalent to the reduction in burden had exposure been limited to temperatures no higher than the TMRED.[9]

For the current study, we defined the TMRED as being the annual mean temperature for the climate zone or state or territory,[19] as the local distribution of minimum mortality temperatures (ie, temperatures at which mortality risk is lowest) is closely linked with annual mean temperature (based on mean of daily maximum and minimum temperatures in the SILO dataset).[20] We calculated the prevalence of exposure to high temperatures during 2014–19 in each climate zone as the proportion of days during the financial year on which the temperature exceeded the TMRED.

We categorised annual mean temperatures by one degree Celsius category and determined the TMRED for each climate zone. To estimate the relative risk (RR) per unit change in temperature, assuming a log-linear relationship between occupational injury and heat, we applied the formula:

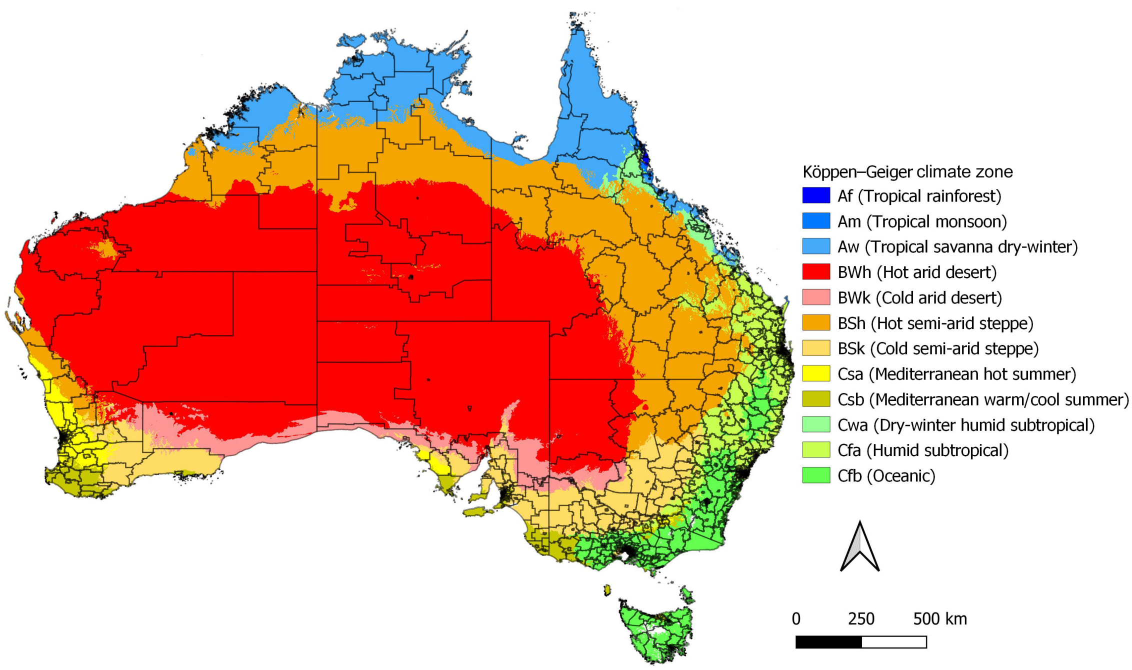
$$RR_{c(z)} = exp\left(ln RR_z \times \left(c - T_z\right)\right), c > T_z$$

in which c is the temperature category, z the climate zone, and T the TMRED (ie, annual mean temperature).

The RRs for heat-associated occupational injury by global climate zone (RR_z) were derived from our recent systematic review and meta-analysis.[21] This report did not include five of the twelve climate zones relevant to Australia (Af, Am, Aw, BWk, Cwa). For the latter two zones, we substituted RR values for similar climate zones: BSk (semi-arid, cold) for BWk (arid, desert, cold) — the two zones have similar mean annual temperatures (16.5°C and 17.8°C respectively) — and Cfa for Cwa (both humid subtropical zones; mean annual temperatures: 19.4°C and 22.6°C respectively). RRs for the Af, Am, and Aw (tropical) climate zones were based on a study of heat-associated occupational injury among sugarcane harvesters in Guatemala,[22] the only relevant published study for this climate zone type.

The population attributable fraction (PAF) for heat-attributable occupational injury was calculated using the comparative risk

1 Köppen–Geiger climate zones of Australia*



* Based on information and data in Beck et al. (2018).[10] ◆

assessment method, based on the increase in RR for occupational injury associated with exposure to the risk factor and the estimated prevalence of exposure:[9]

$$\mathrm{PAF} = \frac{\sum_z P_z\left(\mathrm{RR}_z - 1\right)}{1 + \sum_z P_z\left(\mathrm{RR}_z - 1\right)} \times 100$$

in which z is the index category (climate zone), RR_z is the category-specific relative risk, P_z is the prevalence of exposure to the risk factor in the climate zone, and $\sum_z$ is the sum of the proportion of the year during which the temperature exceeded the TMRED for each categorised temperature value in the distribution and the corresponding estimated RR for the climate zone. Population-adjusted YLDs and YLLs were multiplied by the PAF to calculate the heat-attributable burden of disease by climate zone or state or territory (state heat-attributable DALYs were calculated by aggregating the climate zone-specific DALYs within the state). The heat-attributable occupational injury DALYs were then calculated and expressed as a proportion of all DALYs associated with occupational injury. We also report annual rates of attributable burden of disease per 1000 employed workers.

In sensitivity analyses, median or modal temperatures (most frequent mean daily temperature) were used instead of mean annual temperature for the TMRED, alternative exposure periods, data sources, and exposure–response relationships (including linear and non-linear forms) were examined, and alternative temperature exposure references (mean annual maximum and minimum temperatures rather than annual mean temperatures) used.

Analyses were undertaken in Microsoft Excel 2016 and Python 2.0.

Ethics approval

The University of Adelaide Human Research Ethics Committee granted our negligible risk study an exemption from formal ethics review.

Results

Within each climate zone, the annual mean and median daily temperatures were similar, but modal daily temperatures for the BSk, BWk, Cfb, Csa, and Csb climate zones were markedly lower and that of BWh markedly higher than the corresponding mean and median temperatures. The highest mean temperatures were for the two northern climate zones (Am and Aw) (Box 2; Supporting Information, figure 1).

Total burden of occupational injury by climate zone and state or territory

During 2014–19, an estimated 42 884 years of healthy life were lost to occupational injury, comprising 39 485 YLLs (92.1%) and 3399 YLDs (7.9%). By climate zone, the largest proportions of the national occupational injury burden were in the Cfa (18 836 DALYs; 43.9% of the national total) and Cfb zones (11 881 DALYs; 27.7%) (Box 3). By state and territory, the largest proportions of the national occupational injury burden were in New South Wales (13 095 DALYs; 30.5%) and Queensland (10 473 DALYs; 24.4%). The highest occupational injury burden rate was in the Northern Territory (1.76 DALYs per 1000 workers; Australia: 0.80 DALYs per 1000 workers) (Box 4).

Burden of occupational injury attributable to high temperatures

During 2014–19, 967 occupational injury-related DALYs were attributable to heat (2.3% of occupational injury-related DALYs), comprising 890 YLLs (92%) and 77 YLDs (8%). By climate zone, the heat-attributable proportion was largest in the tropical Am (14 DALYs; 3.5%) and Aw zones (34 DALYs; 3.5%); the largest PAF was for the Am zone (3.3%). The largest number of heat-attributable occupational injury-related DALYs was for the populous humid subtropical Cfa climate zone (622 DALYs; 3.3% of DALYs in Cfa zone, 64% of national total) (Box 5).

By state and territory, the heat-attributable proportions of occupational injury-related DALYs were largest in New South

2 Mean, median, and modal daily temperatures, Australia, 1 July 2014 – 30 June 2019, by Köppen–Geiger climate zone, and relative increase in risk of occupational injury among employed workers per one degree Celsius increase in temperature

	Daily temperature (°C)			
Climate zone	Mean (SD)	Median (IQR)	Mode	Relative risk (95% CI)*
Af (tropical rainforest)	23.7 (2.6)	23.8 (21.2–26.2)	28.0	1.030 (0.940–1.140)†
Am (tropical monsoon)	24.8 (2.4)	24.8 (22.5–27.1)	26.9	1.030 (0.940–1.140)†
Aw (tropical savanna)	26.5 (2.3)	27.4 (24.4–28.4)	27.9	1.030 (0.940–1.140)†
BWh (hot desert)	22.5 (5.6)	23.5 (16.8–27.7)	29.4	1.004 (1.001–1.008)
BWk (cold desert)	18.1 (5.5)	18.5 (12.8–23.1)	11.5	1.005 (1.004–1.005)‡
BSh (hot semi-arid)	22.6 (5.1)	23.6 (17.4–27.4)	28.2	1.005 (1.004–1.007)
BSk (cold semi-arid)	16.8 (5.1)	17.2 (11.6–21.3)	10.8	1.005 (1.004–1.005)
Csa (Mediterranean, hot summer)	18.5 (4.2)	18.3 (14.6–22.4)	14.2	1.009 (1.008–1.011)
Csb (Mediterranean, warm summer)	15.7 (4.0)	15.8 (11.7–19.3)	11.6	1.006 (1.004–1.007)
Cwa (humid subtropical, dry winter)	22.9 (3.4)	23.2 (19.6–26.2)	26.7	1.017 (1.014–1.020)§
Cfa (humid subtropical, hot summer)	19.7 (4.0)	20.1 (15.8–23.5)	23.7	1.017 (1.014–1.020)
Cfb (oceanic, warm summer)	14.5 (3.4)	14.7 (10.1–18.8)	8.3	1.010 (1.008–1.012)

CI = confidence interval; IQR = interquartile range; SD = standard deviation. * Source: Pooled estimates in Fatima et al (2021),[19] except: † Derived from Dally *et al.* (2020).[20] ‡ BSk relative risk used as proxy. § Cfa relative risk used as proxy. ◆

3 Burden of occupational injury, Australia, 1 July 2014 – 30 June 2019, by Köppen–Geiger climate zone

Climate zone	Employed workers*	Years of life lost	Years lived with disability	Disability-adjusted life years (national proportion)
Australia	10 669 078	39 485	3399	42 884
Af (tropical rainforest)	8981	34	3	37 (0.1%)
Am (tropical monsoon)	85 359	319	27	346 (0.8%)
Aw (tropical savanna)	239 161	885	76	961 (2.2%)
BWh (hot desert)	101 765	377	32	409 (1.0%)
BWk (cold desert)	42 557	157	14	171 (0.4%)
BSh (hot semi-arid)	125 053	463	40	503 (1.2%)
BSk (cold semi-arid)	882 750	3267	281	3548 (8.3%)
Csa (Mediterranean, hot summer)	1 062 013	3930	338	4268 (10.0%)
Csb (Mediterranean, warm summer)	422 574	1564	135	1699 (4.0%)
Cwa (humid subtropical, dry winter)	57 815	214	18	232 (0.5%)
Cfa (humid subtropical, hot summer)	4 685 128	17 343	1493	18 836 (43.9%)
Cfb (oceanic, warm summer)	2 955 922	10 940	942	11 882 (27.7%)

* Employed labour force in 2016.[17] ◆

4 Burden of occupational injury, Australia, 1 July 2014 – 30 June 2019, by state and territory

State/territory	Employed workers	Years of life lost: Number (national proportion)	Years of life lost: Annual rate, per 1000 workers	Years lived with disability: Number (national proportion)	Years lived with disability: Annual rate, per 1000 workers	Disability-adjusted life years: Number (national proportion)	Disability-adjusted life years: Annual rate, per 1000 workers
Australia	10 669 078	39 485	0.74	3399	0.06	42 884	0.80
New South Wales	3 376 865	11 947 (30.3%)	0.71	1148 (33.8%)	0.07	13 095 (30.5%)	0.77
Victoria	2 734 079	7838 (19.9%)	0.57	615 (18.1%)	0.04	8453 (19.7%)	0.62
Queensland	2 133 275	9702 (24.6%)	0.91	771 (22.7%)	0.07	10 473 (24.4%)	0.98
Western Australia	1 155 659	5126 (13.0%)	0.89	462 (13.6%)	0.08	5588 (13.0%)	0.97
South Australia	745 357	2711 (6.9%)	0.73	223 (6.6%)	0.06	2934 (6.8%)	0.79
Tasmania	216 325	1102 (2.8%)	1.02	80 (2.4%)	0.07	1182 (2.8%)	1.09
Northern Territory	102 100	847 (2.1%)	1.65	58 (1.7%)	0.11	905 (2.1%)	1.76
Australian Capital Territory	205 418	212 (0.5%)	0.21	42 (1.2%)	0.04	254 (0.6%)	0.25

Wales and Queensland (each 2.9%). The largest numbers of heat-attributable occupational injury-related DALYs were also in New South Wales (379 DALYs; 39% of national total) and Queensland (309 DALYs; 32% of national total); the smallest was in the Australian Capital Territory (5 DALYs; 0.5% of national total). The highest heat-attributable occupational injury burden rate was in the Northern Territory (0.04 DALYs per 1000 workers per year; Australia: 0.02 DALYs per 1000 workers per year) (Box 6).

Sensitivity analyses

Sensitivity analyses using different TMRED indicators yielded slightly different heat-attributable DALY proportions for Australia (1.8–3.0%), but they were generally of similar magnitude to the proportion in our major analysis (2.3%) (Supporting Information, table 1).

Discussion

We found that Australian workers lost 42 884 years of healthy life to occupational injuries during 2014–19, an annual rate of 0.80 DALYs per 1000 workers. Heat-related occupational injuries caused the loss of 967 DALYs (2.3% of all occupational injury-related DALYs). The relative risks per degree increase in temperature exposure for heat-associated occupational injury obtained from the systematic review and meta-analysis were highest in the two tropical climate zones (Am, Aw),[19] and the proportions of DALYs that were heat-attributable were also

5 Population attributable fraction (PAF) and heat-attributable burden of occupational injury (disability-adjusted life years, DALYs), Australia, 1 July 2014 – 30 June 2019, by Köppen–Geiger climate zone

			Heat-attributable burden of occupational injury			
Climate zone	Occupational injury-related DALYs	PAF	Years of life lost	Years lived with disability	DALYs (proportion of all DALYs)	Annual DALY rate (per 1000 workers)
Australia	42 884		890	77	967 (2.3%)	0.02
Af (tropical rainforest)	37	2.5%	1	0	1 (2.7%)	0.02
Am (tropical monsoon)	346	3.3%	13	1	14 (3.5%)	0.03
Aw (tropical savanna)	961	2.3%	32	2	34 (3.5%)	0.03
BWh (hot desert)	409	0.8%	4	0	4 (1.0%)	0.01
BWk (cold desert)	171	1.1%	2	0	2 (1.2%)	0.01
BSh (hot semi-arid)	503	1.0%	6	0	6 (1.2%)	0.01
BSk (cold semi-arid)	3548	1.1%	33	3	36 (1.0%)	0.01
Csa (Mediterranean, hot summer)	4269	1.4%	66	6	72 (1.7%)	0.01
Csb (Mediterranean, warm summer)	1699	0.8%	13	2	15 (0.9%)	0.01
Cwa (humid subtropical, dry winter)	232	1.9%	5	0	5 (2.2%)	0.02
Cfa (humid subtropical, hot summer)	18 836	3.1%	571	51	622 (3.3%)	0.03
Cfb (oceanic, warm summer)	11 881	1.7%	144	12	156 (1.3%)	0.01

6 Heat-attributable burden of occupational injury (disability-adjusted life years, DALYs), Australia, 1 July 2014 – 30 June 2019, by state and territory

		Heat-attributable burden of occupational injury			
State/territory	Occupational injury-related DALYs	Years of life lost	Years lived with disability	DALYs (proportion of all DALYs)	Annual DALY rate (per 1000 workers)
Australia	42 884	890	77	967 (2.3%)	0.02
New South Wales	13 095	346	33	379 (2.9%)	0.02
Victoria	8453	123	10	133 (1.6%)	0.01
Queensland	10 473	286	23	309 (2.9%)	0.03
Western Australia	5588	69	6	75 (1.3%)	0.01
South Australia	2934	27	2	29 (1.0%)	0.01
Tasmania	1182	18	1	19 (2.0%)	0.02
Northern Territory	905	17	1	18 (2.0%)	0.04
Australian Capital Territory	254	4	1	5 (2.0%)	0.00

largest in these two zones (each 3.5%). The highest heat-related occupational injury DALY rate per 1000 workers was in the Northern Territory, where factors other than temperature, including remoteness and access to health care, are probably further contributing factors.

Our results are consistent with those of studies that have used other methods to estimate the fraction of occupational injury attributable to heat. For example, we found that 2.0% of workers' compensation claims in Adelaide (climate zone Csa) during 2003–2013 were attributable to high temperatures;[1] our estimate for the Csa climate zone in the current study was 1.7% of occupational injury-related DALYs. Similarly, studies from Spain (primarily Csa)[7] and Italy (primarily Csb)[23] respectively reported heat-attributable fractions of 0.8% and 1.8%.

Heat-related morbidity and mortality are expected to increase in Australia because of global warming, exacerbating productivity losses for industries involving outdoor labour.[24] Construction workers in Australia lost 67 565 hours of work because of heat stress (working in direct sunlight) during 2019, more than twice the 10-year mean of 25 240 hours during 1991–2000,[25] indicating the importance of investigating the impact of climate change on health in burden of disease studies.

Estimating the theoretical minimum level of population exposure beyond which disease or injury risk increases is critical for estimating factor-attributable burdens, and relatively small differences in the TMRED can markedly alter PAF estimates.[26] However, determining the temperature associated with the lowest risk of heat exposure-related occupational injury is difficult, as thresholds vary by location and health outcome. Climate zones may provide a useful framework for estimating burden of disease and heat exposure at the sub-national level.

Limitations

Firstly, PAF calculations were based on RRs derived from a systematic review and meta-analysis of overseas data,[21] and we assumed that these RRs applied to similar Australian climate zones. Most of the RRs we adopted were derived from data for countries with climate and socio-economic characteristics similar to those of Australia, but some were derived from data for countries with similar climate but different socio-economic profiles (eg, Guatemala,[22] used for Australian tropical zones). However, cross-validation of the RRs used with unpublished data from Australian studies indicated that they were consistent with local conditions (data not shown). Further, for each zone the same RR was used to estimate the PAF for calculating both the heat-attributable YLLs and YLDs, as the reviewed studies did not distinguish between fatal and non-fatal occupational injury burden.[21]

Secondly, we used the annual mean temperature for the TMRED, as other studies have found that the association of mortality with annual mean temperature is a reasonable indicator of population adaptation.[18,20] Cross-validation of TMRED with exposure–response curves from our earlier study[2] and for other Australian cities (unpublished data) indicated that the temperatures associated with lowest occupational injury risk closely matched the annual mean temperature in each climate zone we examined (data not shown). Further, sensitivity analyses using alternative temperature measures yielded results similar to those of our main analysis.

Thirdly, we did not consider adaptation or acclimatisation in our analysis, nor restricted access to health care in regional and remote areas. Fourth, as the heat-attributable occupational injury burden may differ by specific location within climate zones or jurisdictions, our estimates cannot be applied to specific locations in heterogeneous urban or sparsely populated regional or rural areas. Our findings may also have been influenced by industries with workers at greater risk of heat exposure, such as agriculture or mining. Finally, demographic, health, and socio-economic differences were not considered by our analysis, nor did we stratify our analyses by sex, age, or occupational characteristics.

Conclusion

Despite these caveats, our estimates suggest that the impact of high ambient temperatures on occupational injury in exposed workers is not trivial. Our study, one of the first to estimate the burden of heat-attributable occupational injury, highlights a problem that will increase as temperatures rise with climate change. It is imperative that workplace health and safety be safeguarded during extreme heat, as is protecting workers in industries such as agriculture, transport, and construction, and those in poorly ventilated indoor workplaces. Measures could include restructuring of work hours, providing adequate rest breaks, shaded or cooled rest areas, cool drinking water, personal protective equipment, and wearable cooling devices, and use of health monitoring technologies.

We have quantified the impact of high ambient temperatures on the occupational injury burden in the twelve climate zones of Australia. During 2014–19, 2.3% of the national occupational injury burden was attributable to heat exposure, and the proportion was larger in the tropical climate zones (Am and Aw) and in the Northern Territory. Without adaptive measures and industry-based policies, the heat-attributable occupational injury burden will increase as climate change advances.

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Supporting Information

Additional Supporting Information is included with the online version of this article.