

Deadly heat stress conditions are already occurring

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Heat stress limits for human survivability have been previously defined by a 6-hour exposure to a wet-bulb temperature of 35°C. However, the recently developed physiology-based HEAT-Lim model demonstrates that environmental heat stress thresholds may be cooler and drier than previously thought. We employ HEAT-Lim to determine whether non-survivable thresholds were surpassed during six historical events where conditions were climatologically extreme and/or high heat-related mortality was reported. Our results show that non-survivable conditions are occurring during present-day heat events, all of which are below 35°C wet-bulb temperature. Of concern is regular exceedances of deadly thresholds for older people directly exposed across all events. Moreover, extremely hot yet dry conditions are found to be just as deadly as hot and humid conditions. For future climatological assessments, we emphasise the importance of employing increasingly accurate physiology-derived methods to assess the risk of potentially deadly heat stress.

Heatwave intensity, frequency and duration have increased almost everywhere since at least the 1950s^{1,2}, with trends accelerating in recent decades¹. Coincident is the increasing occurrence of record-shattering heatwaves³, breaking previous records by large margins^{4–10}. Recent heatwaves have inflicted high human mortality rates^{11–20} disproportionately impacting low-latitude and/or developing countries^{13–16,19,20}, underlining the inequity of extreme weather and climate events. Additionally, adverse health impacts are disproportionately visited upon physiologically vulnerable groups such as the elderly²¹, pregnant people²² and younger children²³, those with underlying chronic diseases^{21,24}, and those who cannot access adequate cooling because of economic limitations^{24–29}.

Epidemiological studies show that high temperatures and extreme heat events cause a rise in heat-related mortality, both in the historical period and under contemporary anthropogenic climate

change^{30–36}. While these studies are important for determining baseline influences of temperature on mortality, they commonly do not account for the crucial role humidity plays in determining how survivable extreme heat events can ultimately be^{37–40}. When humidity is high, it is progressively difficult for the human body to shed excess heat via the evaporation of sweat from the surface of the skin²⁴. When humidity is low, the maximum capacity of humans to produce sweat in the first place limits their ability to keep cool³⁹; thus, accounting for all levels of atmospheric moisture in modelling the human tolerance to extreme heat is vital. As internal body temperatures rise, the risk of advanced heatstroke climbs until it becomes almost inevitable at a human core temperature of 43 °C. The combinations of temperature and humidity required for heatstroke to occur depend on exposure duration as well as the ability of the person to sweat. Standard measurements of ambient temperature are done under conditions that

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protect instruments from direct radiant thermal load (e.g., sun radiation) while allowing air to flow through to avoid overheating from stagnant air. However, sun exposure further increases human heat stress risk, and its inclusion in heat stress modelling through the estimation of mean radiant temperature⁴¹ conveys more realistic exposures for heat risk in outdoor environments. Accounting for thermal radiation from sunlight is therefore crucial.

Wet bulb temperature (T_w) is one of a number of meteorological metrics⁴² employed to assess how humans may be impacted by various combinations of ambient temperature and humidity. A seminal study, Sherwood and Huber 2010⁴³, theorised that exposures become non-survivable at a T_w of 35 °C sustained for 6 h due to the elimination of sensible and latent heat dissipation from the skin surface of humans. It is important to emphasise that this study proposed T_w of 35 °C as a fundamental limit, survivable only via access to air conditioning. Over the past decade, numerous climate-led assessments have adopted the T_w of 35 °C limit to understand historical and future changes in human survivability due to heat stress^{44–49}. However, despite its strong biophysical rationale, the T_w 35 °C model does not impose any limits to important physiological mechanisms, such as evaporative cooling via sweating^{50–52}. Recently, the Arizona State University /University of Sydney Human/Environmental Adaptation and Threshold Limits Model (hereafter HEAT-Lim; Vanos et al³⁹) proposed a revised model of physiological limits incorporating key human physiological principles. In HEAT-Lim, the human heat stress limits for survival due to heat stroke are much lower than T_w 35 °C^{38,39,43,51}, which can be further categorised by age and access to shade³⁹. The difference between these critical combinations of temperature and humidity for human survival and the traditional T_w 35 °C become progressively greater at high temperatures with low humidity (Fig. 1) and when sun-exposed. This disparity between models widens further for adults aged >65 years compared to younger adults aged 18–35 years (Fig. 1) due to age-related sweating decrements.

In this study, we investigate whether physiology-based heat stress limits determined using HEAT-Lim have already been breached during record-breaking heatwaves across the world^{12,17,18,53–59}, many of which resulted in high mortality rates^{12,17,18,58–60} yet did not yield sustained T_w 35 °C conditions. Comprehensive epidemiological evidence demonstrates that heat-related mortality has repeatedly occurred without T_w 35 °C being breached or sustained^{11–17,20,24,30–36,61}, and we demonstrate here that deaths associated with six historical heatwaves coincide with

exceedances of the HEAT-Lim thresholds, whereas T_w 35 °C fails to predict deadly conditions accurately (i.e., falling into the yellow sections of Fig. 1). Furthermore, while T_w values close to 35 °C have previously, yet briefly, been recorded at local meteorological sites⁶¹, no study has yet investigated whether deadly combinations of heat and humidity—including those below and/or drier than the often-cited 35 °C T_w threshold—have persisted long enough for heat stroke to evolve and be fatal^{24,37–40}.

Results

Observed heatwaves in the context of non-survivability for older people

As climate change intensifies, heatwaves are occurring more often and becoming more extreme^{1,2}, providing a larger sample from which to draw case studies. We focus our analysis on six events, chosen due to a combination of the following factors: 1) high rates of reported all-cause mortality, 2) intense and persistent extreme heat, and 3) climatologically extreme temperatures, often record-breaking, at the time of occurrence. Table 1 lists these events, the regional boundaries and dates over which they were assessed, as well as meteorological statistics and reported deaths. With the exception of Australia, most events are associated with at least 1000 deaths, and with the exception of Europe, most events persisted for at least three weeks^{11–20}. We include Australia in our study due to the record-breaking nature of intense and widespread heat⁵⁵, and include Europe for both its record-breaking temperatures and extremely high associated mortality⁵³. Moreover, all events did not exceed T_w 35 °C despite high reported rates of heat stroke, thereby providing a basis to determine whether HEAT-Lim limits³⁹ were indeed breached.

Each event presents a unique signature in terms of non-survivable days as defined by HEAT-Lim³⁹ for older people situated in direct sun (i.e., in direct sunlight without shade)³⁹ overlaid with the respective demographic population density per square kilometre (Fig. 2). People over 65 y faced an extremely high risk of physiological heat stress should they have not sought shade or cooling during the examined historical heatwaves over the Middle East, Southern Asia, Central America, Australia and India/Pakistan (Fig. 2b–f). All but one event analysed (Europe 2003, Fig. 2g) experienced large areas where the proportion of non-survivable days for people over 65 y was at least 25%, and regularly over 50%. Over the Middle East (2b), Central America (2d) and Australia (2e), while the non-survivability for people

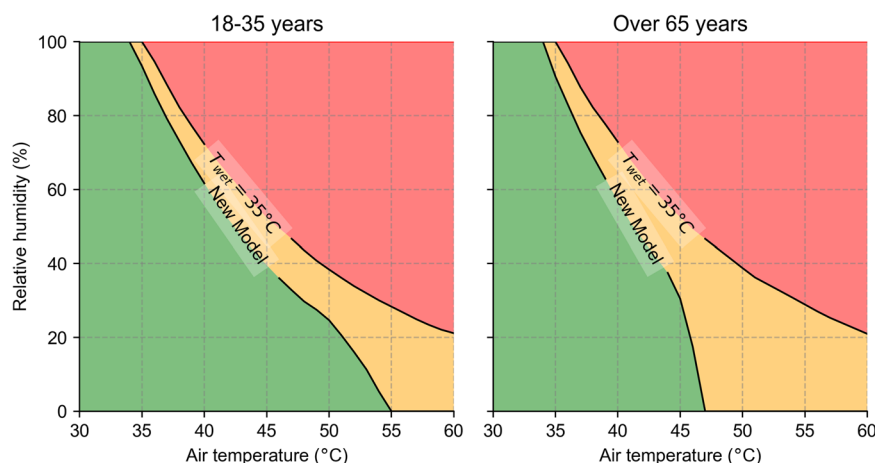


Fig. 1 | Comparison of non-survivable heat stress thresholds. Limits of survivability based on the combination of temperature and humidity produced by the physiology-based model (HEAT-Lim³⁹) and the traditional T_w 35 °C⁴³ model for younger adults (left) and older adults (right) for 6 h of continuous exposure (in shade). The green area (on the left-hand side of each graph) indicates conditions are survivable with both models. The red area (on the right-hand side of each graph)

indicates conditions are non-survivable for both models. The yellow area indicates the difference between the two—i.e., conditions modelled to be non-survivable with the physiology-based model³⁹, but considered survivable with the T_w 35 °C model⁴³. Note: the difference (yellow area) expands at higher ambient temperatures with lower relative humidity, and with age.

Table 1 | Information on each historical heat event analysed

Region	City/ population	Dates	Highest Dry-bulb Temperature (°C) & corresponding humidity (%)	Highest Wet-bulb Temperature (°C)	Reported Deaths
Middle East	Mecca: 21.42°N; 39.18°E Population 2.1 M	June–July 2024	44.61; 18.37 (05/06/24)	29.47 (19/06/2024)	During Hajj (the 14 th –19 th June), over 1300 deaths related to heat were reported ⁶¹ .
SE Asia	Bangkok: 13.76°N; 100.5°E Population 11.2 M	April 2024	41.66; 43.71 (27/04/24)	28.73 (27/04/24)	At least 1473 deaths in Southeast Asia, around 60 deaths in Thailand ¹⁸ .
USA/Mexico	Phoenix: 33.45°N; 112.07°W Population 1.66 M	June/ July 2023	46.72; 10.46 (21/07/23)	24.32 (16/07/23)	In 2023, 2325 died from heat stress in the USA ⁹⁶ . Around 250 deaths in Mexico during June/July ²⁰ .
Australia	Mount Isa: 20.72°S; 139.49°E Population 18,000	January 2019	41.53; 12.01 (24/01/19)	25.08 (11/01/19)	None reported
India/Pakistan	Larkana: 27.55°N; 68.2°E Population (district) 1.7 M	June 2015	46.68; 18.26 (20/06/2015)	30.85 (20/06/2015)	Estimated 2000 deaths in Pakistan ⁹⁷ , estimated 2500 deaths in India ⁹⁸ .
Europe	Seville: 37.39°N; 5.98°W Population 700,000	July August 2003	42.62; 20.48 (01/08/03)	26.23 (02/08/2003)	Estimated 70,000 deaths throughout Europe ⁹⁹ .

For each event, we provide the timing of the event, reported mortality, the name and location of the example city chosen to represent the event's meteorology and its population, as well as the maximum 6-hourly mean air temperature and corresponding 6-hourly relative humidity, and maximum 6-hourly mean wet-bulb temperature over each city during the event. All meteorological values are extracted from ERA5 ("Methods").

in direct sun over 65 y was reasonably high (between 25–75% of all six-hourly windows), the corresponding population density for the same age group was consistently less than five people/km². However, the opposite was true during the Southern Asia and India/Pakistan events (Fig. 2c, f), where the density of people over 65 y is consistently over 10 people/km², with large regions of 50–100 people/km². Coupled with high percentages of non-survivable days, these events were extremely deadly for older people in direct sun, no doubt contributing to reported elevated death tolls formally associated with these events^{12,17,18,55,56,58} (Table 1). While the 2024 Middle Eastern event (Fig. 2b) was not associated with a high permanent population density of older people, non-survivable days for the demographic were largely in excess of 75%. This finding is pertinent given the performance of Hajj aligning with the heatwave^{18,59–61}, a multi-day Muslim pilgrimage to Mecca that is attended by older generations in high numbers^{59–61}, with pilgrims crossing large distances over the Middle East, Africa and West Asia to attend^{62–64}. Despite meticulous planning to mitigate against heat-related impacts during this event⁶⁵, a relatively high number of deaths still occurred due to a combination of the sheer volume of people attending and the levels of inevitable heat exposure. Indeed, without this noteworthy effort, recorded heat exposure cases during Hajj in 2024 could have undoubtedly been much higher.

In contrast, the European 2003 event (Fig. 2g) consisted of only small regions where non-survivable days for older people in direct sun were up to 25% and were coupled with low population density of the same age group. Initially, this finding is surprising, particularly given the 70,000+ excess deaths associated with the event, with France recording the highest national death toll^{12,65}. While a measure of excess mortality is not straightforward to compare to the more specific interaction of heat stress on mortality³⁹, the demographic most affected during the European 2003 heatwave was older people⁶⁶ for which there was a 70% and 120% increase in excess deaths for the 75–94 years and over 94 years age groups, respectively⁶⁵. Most deaths during the 2003 European event were likely cardiovascular- or respiratory-related, which often occur below a core body temperature of 43 °C (e.g., in France 2003, 30% of excess deaths were cardiovascular/respiratory-related, while 11.5% were heatstroke or hyperthermia⁶⁷). HEAT-Lim assumes that a core temperature of 43 °C is what results in death (i.e., heatstroke); thus, we are modelling heat stroke deaths only, and not those caused by other conditions that may

be brought on by the extreme conditions³⁹. Moreover, HEAT-Lim does not include a cumulative factor; that is, it assumes that individuals are normothermic at the start of each six-hour exposure window. Continuous exposure to ambient conditions likely instead elevates core body temperature above the starting value used in the model (36.8 °C). For example, core temperature elevations of 0.5–1.0 °C have been observed after 3-h exposure to 45 °C with 15% relative humidity⁶⁸, the temperature/humidity thresholds required to induce heat stroke could therefore likely be cooler and drier than in our analysis. This is another possible factor that was at play during the 2003 European heatwave.

Additionally, the meteorological signature during the 2003 European heatwave included a stubborn blocking high-pressure system, permitting persistently hot yet very dry conditions for over a week⁵³, thus reducing the humidity component in determining physiological stress, resulting in corresponding T_w values well below 35 °C. ERA5's assimilation, which relies on non-urban in-situ records, can result in heatwaves over European cities being 5–7 °C cooler relative to local observations⁶⁹, suggesting that city-scale temperatures during the 2003 event were higher in reality than in ERA5. Therefore, if consistent values of relative humidity occurred, higher local temperatures may have driven more occurrences of non-survivable conditions across European urban areas than what ERA5 predicts. We test this by comparing the physiology-based HEAT-Lim thresholds during the 2003 European heatwave for the ERA5 gridcell over Seville and the corresponding in-situ station that contributes to the Integrated Surface Dataset⁷⁰ (ISD, "Methods"; see Supplementary Information). We find that ERA5 underestimates daily extreme temperatures in Seville during the 2003 heatwave by up to 3 °C. This results in a discrepancy of non-survivable conditions for older people in direct sun, with more days experiencing non-survivable conditions during the most extreme period per day when assessed using the ISD local station (Fig. S1f) vs ERA5 (Fig. 3f). Thus, the likely hotter conditions over all affected European urban environments—which is where the vast majority of people live and work—could have contributed to increased heat stress conditions during the 2003 event.

We emphasise that just one 6-hour period above a physiological survivability heat threshold³⁹ ("Methods") inflicts truly detrimental and irreversible damage, even when the outcome is not fully realised for multiple days. The physiological thresholds used in this study from HEAT-Lim are grounded in human heat balance modelling and the

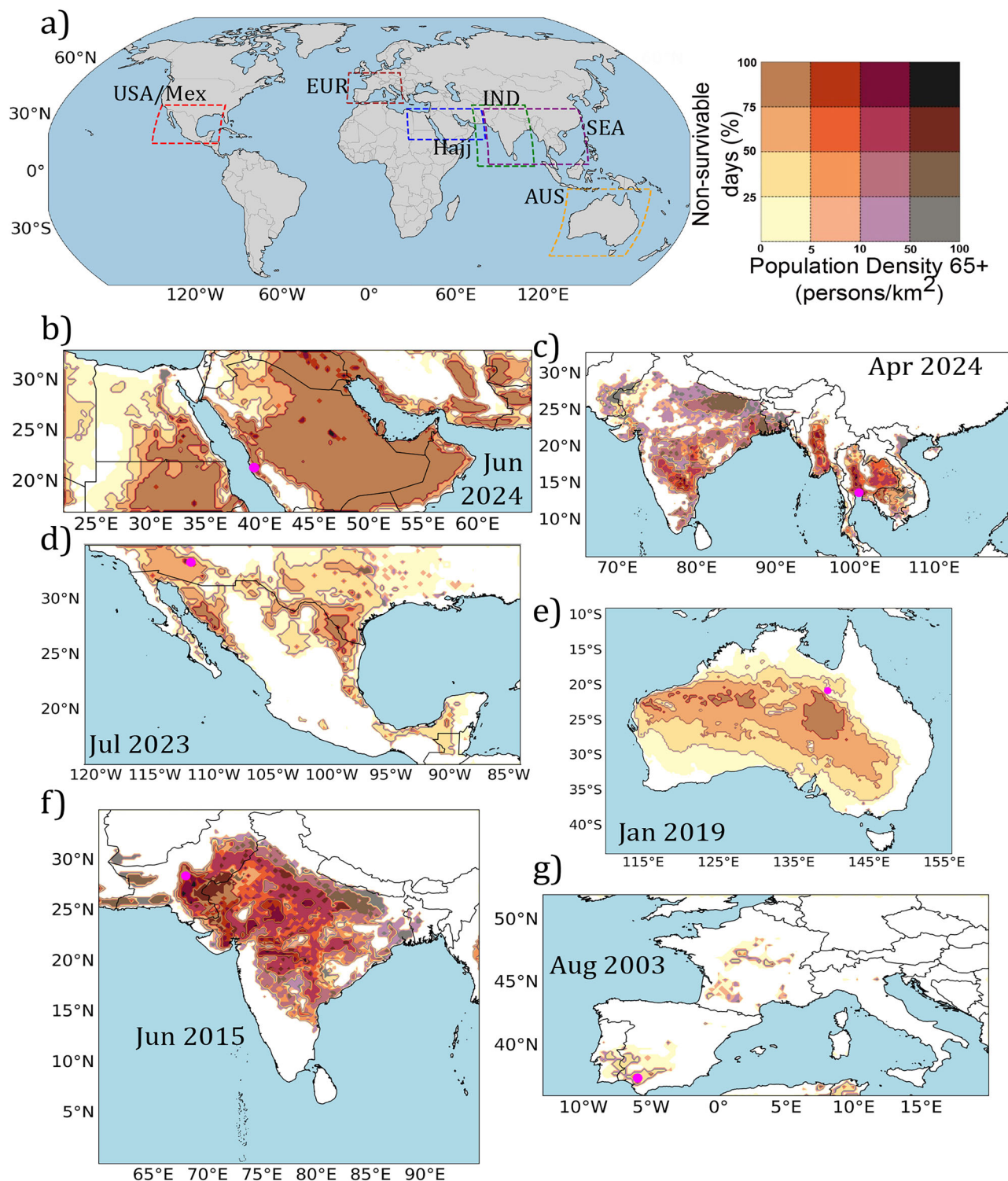


Fig. 2 | Non-survivable conditions for older people in direct sun. The proportion of non-survivable conditions during historical and extreme heat waves for older people (65+) in direct sun computed from ERA5, combined with estimated population density for the same age group computed from WorldPop; **a** the location of each historical event analysed; **b** the Middle East heat wave during June 2024; **c** the South Asian heatwave of April 2024; **d** the North and Central American heat wave during July 2023; **e** the Australian heatwave during January 2019; **f** the Indian heatwave during June 2015; and **g** the European heatwave during August 2003. Yellow indicates combined low population (<math><5</math> persons/km²) and proportion of

non-survivable days (<math><25\%</math>), whereas black indicates combined high population (50–100 persons/km²) and proportion of non-survivable days (>75%). All other colours indicate a progressive and increasing combination of the two variables, reaching darker shades when variable values increase. The location of each city examined in greater detail for the observed event and future projections is indicated by the magenta dot. For specific details of each event, its location, and corresponding city, please see Table 1. Please see “Methods” for details regarding ERA5, WorldPop, and non-survivability calculations.

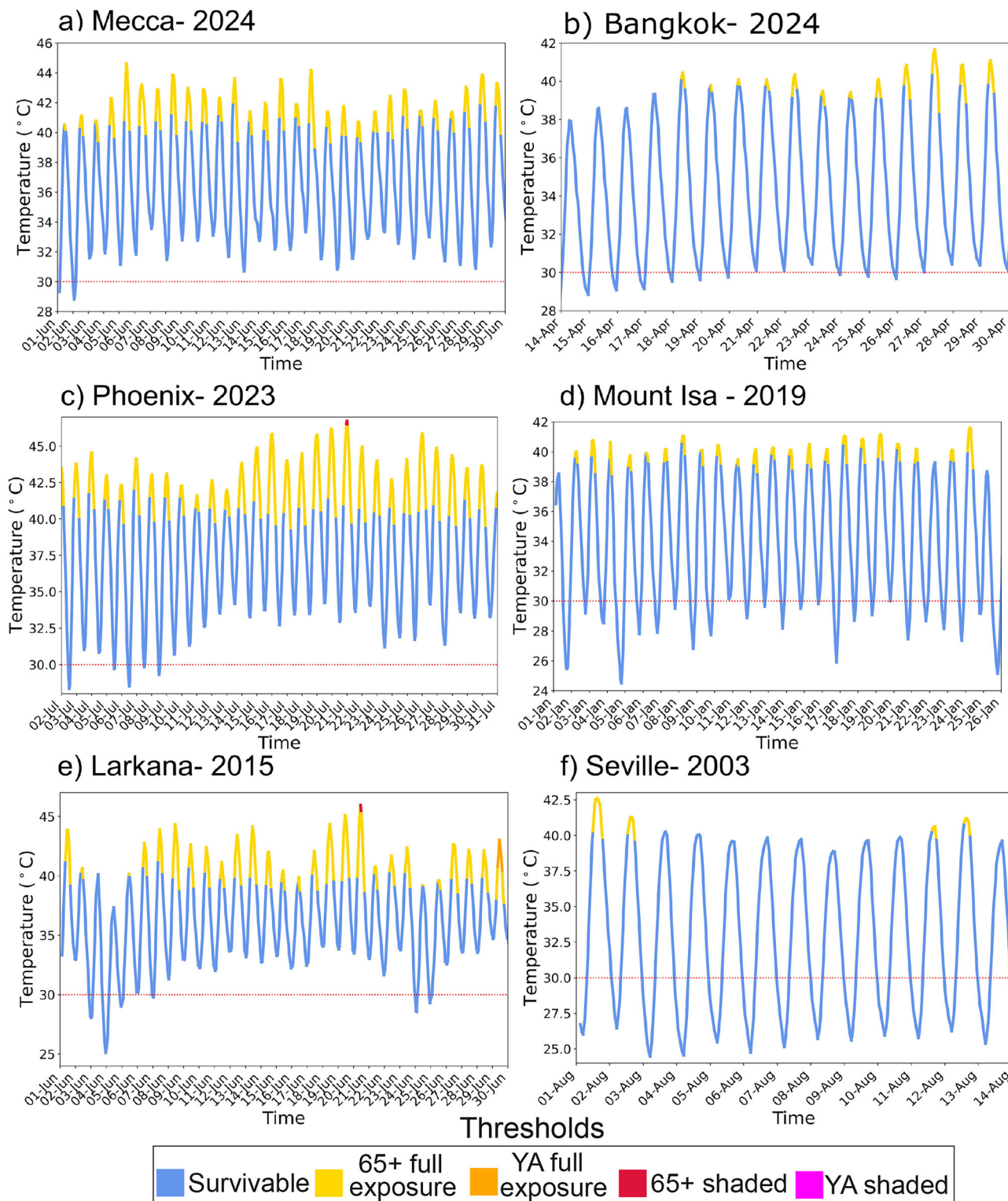


Fig. 3 | Six-hourly temperature time series for each heatwave studied. Time series of six-hourly temperature for each historical heatwave from ERA5 for each city when non-survivable conditions identified by HEAT-Lim occurred: **a** Mecca during June 2024; **b** Bangkok during April 2024; **c** Phoenix during July 2023; **d** Mount Isa during January 2019; **e** Karachi during May and June 2015; **f** Seville during August 2003. Based on the corresponding relative humidity, each plot depicts whether conditions were physiologically survivable for all (blue), non-

survivable for older people in direct sun (yellow), non-survivable for younger people in direct sun (orange), non-survivable for older people seeking shade (red), or non-survivable for younger people seeking shade (purple). Should purple be visible, conditions were non-survivable for all people, whether they are seeking shade or fully exposed. For more details on ERA5 and the computation of physiological heat stress thresholds, please see “Methods”. For more details on the respective historical events, please see Table 1.

associated transfer of heat from the body into the broader environment, and the physiological level of heat strain (core temperature) that causes fatal heat stroke^{24,37–40}. Additionally, contemporary reanalysis products such as ERA5 (“Methods”) now provide data on appropriate temporal and spatial scales with higher accuracy than previous generations⁶⁵. Our analysis, therefore, provides far greater precision in predicting the impact of heat stress than previous methods could achieve^{30–36,43}.

This notable increase in accuracy and confidence in both climatological and physiological methods is important for multiple reasons. First, it suggests that historical heat stress mortality in densely populated, low-latitude, and developing locations is undoubtedly and seriously underreported⁷⁰. Second, it explains previously reported heat-related deaths, particularly those in older demographics, despite associated conditions being well under sustained T_w 35 °C conditions (Fig. 4). Third, extreme and deadly conditions for a considerable amount of the global population are already occurring across various geographic locations at our current global warming level^{71,72} (1.1 °C)—a fraction of the warming that previous estimates suggested could be problematic for widespread heat stress mortality⁴³. While the majority of adverse conditions displayed in Fig. 2 can be adapted to by seeking shade^{73,74} or by simple mechanical⁷⁵ cooling practices, we stress the importance of guaranteeing universal access to such resources and understanding specific contexts that may prevent people from using them. We therefore argue that to best understand the overall risk of deadly heat stroke, outdoor exposure must always be considered.

The consideration of adaptation can be examined by exploring non-survivable thresholds of people seeking shade^{39,73,74}. Should older people have been able to seek shade during the six observed heatwaves studied, the exposure to non-survivable conditions is considerably reduced in all cases (Fig. 4). Over The Middle East (Fig. 4b), non-survivable conditions for people over 65 y drop markedly to no more than 50% of days, half the amount when full sun exposure to outdoor conditions is considered (Fig. 2b). Similarly for the Asian (Fig. 4c) and India/Pakistan (Fig. 4f) events, there is a reduction of non-survivable conditions for older people to no more than 50% of days, but largely to 25%, down from 75–100% of days should the demographic be fully exposed (Fig. 2c, f, respectively). Both the Central American (Fig. 4d) and Australian (Fig. 4e) events were associated with no more than 25% of days considered non-survivable for older people seeking shelter, and the European event (Fig. 4g) was associated with barely any non-survivable conditions for this demographic when seeking shade. These results critically highlight the imperative role of adaptation—by seeking shade and/or introducing effective behavioural adaptation strategies^{39,73–75}, exposure to deadly heat stroke can be dramatically reduced, and therefore has a substantial impact on the number of lives lost. An alternative viewpoint is, should less shade or behavioural cooling mechanisms have been available during any of these historical events (in some cases, access to such mechanisms was already limited^{15–19}), the death toll of those over 65 y could have been much higher than what occurred, because of the physiological effects of sustained exposure to high ambient temperature and/or humidity.

City-scale survivability

We now focus on exceedances of non-survivable physiology-based thresholds over cities during each of the case study events computed from the corresponding grid cell in ERA5 (Figs. 3, 5; “Methods”). We also replicate these calculations using the ISD⁷⁰ in-situ local stations (“Methods”), which are presented in Fig. S1 in the Supplementary Information, along with a comparison across the two datasets. Analogous to Figs. 2, 4, each examined city also experienced multiple and often regular occurrences of deadly conditions for older people in direct sun during the corresponding heatwave. For the 65 y demographic in direct sun, all cities experienced deadly conditions according to HEAT-Lim thresholds at some point during the respective

heatwave. The highest frequency of deadly conditions occurred in Phoenix during July 2023 (Figs. 3c, 5c, S1c), with conditions exceeding the corresponding physiological survivability threshold for 24% (28% based on station data) of rolling 6-h periods during the month-long event. This is an important finding since it highlights that extremely hot and dry conditions can be just as deadly as hot and humid conditions, a consideration that is just beginning to be examined in climate studies in understanding human physiological tolerance to extreme ambient conditions^{39,76}. During this event, there was a single six-hourly period where conditions were non-survivable for older people seeking shade. Mortality data from the summer of 2023 in the region⁷⁷ report that ~60% of heat-related deaths (365 deaths) were among those 50 years or older, with 89% of those deaths occurring indoors. Moreover, while younger people were not exposed to non-survivable heat stress during this Phoenix event, it is very likely that their physiological liveability estimated by HEAT-Lim³⁹ (i.e., the capacity to carry out everyday activities without elevated heat stress risk) was challenged.

Larkana experienced similarly stark conditions during May/June in 2015 (Figs. 3e, 5e, S1e), with 18% (13% based on station data) of rolling 6-hourly blocks above the survivable limits for older people in direct sun. There was also a 6-hourly period where conditions were non-survivable for older people accessing shade, as well as an 18-hour window towards the end of the event where younger people in direct sun were also at risk. Over Mecca in June 2024 (Figs. 3a, 5a, S1a), 12% (10% based on station data) of all rolling 6-hourly blocks over the 30-day period were deadly to older people in direct sun. It is worth reemphasising that just one 6-hourly period where HEAT-Lim thresholds are exceeded can be deadly for a normothermic individual, and Phoenix (Figs. 3c, 5c, S1c), Larkana (Figs. 3e, 5e, S1e) and Mecca (Figs. 3a, 5a, S1a) all experienced conditions that were consistently dangerous during daytime for an entire month, potentially driving the majority of reported¹⁸ and also unreported deaths caused by these events. In order to illustrate more nuanced temporal effects that capture cumulative heat strain over longer exposure times, future research studies could utilise other existing physiological models such as the Gagge 2-node model or the Predicted Heat Strain model⁷⁸. However, these models should be applied with caution under extreme heat and humidity conditions, as they have been developed for, and thus far validated in, participants reaching core temperatures of <39 °C. Existing data supporting these models in older adults is also currently sparse.

A similar situation was also apparent over Bangkok in April 2024 (Figs. 3b, 5b, S1b), Mount Isa in January 2019 (Figs. 4d, 5d, S1d) and Seville in August 2003 (Figs. 3f, 5f, S1f), where older people in direct sun were at serious risk yet at a lower frequency than Mecca (Figs. 3a, 5a, S1a), Phoenix (Figs. 3e, 5e, S1e) and Larkana. For these heatwaves, younger people were not subject to non-survivable conditions, although their functioning at liveable thresholds could have been considerably challenged³⁹. It is worth noting that for all events crossing non-survivable thresholds mainly occurred during the day, with nighttime reprieves evident throughout each event. Over Seville (Figs. 3f, 5f, S1f), there were fewer occurrences of non-survivable limits overall, however, according to ERA5 (Fig. 3f), there were multiple days where the worst daytime and nighttime conditions were dangerously close to non-survivable heat stress levels for older people in direct sun, one of the likely drivers of the high numbers of casualties associated with this event^{18,19}. Indeed, the total number of non-survivable periods for older people outdoors was higher in ERA5 (1%) compared to the local ISD station (0.5%), despite the presence of a cool bias in ERA5 in daytime maximum temperatures (Figs. 3f, S1f).

Also evident from Figs. 3, 5, and S1 are the different combinations of temperature and humidity resulting in each physiological threshold either being exceeded or not. For example, 6-hourly blocks over Bangkok (Figs. 5b, S1b) are more humid yet mostly cooler than over Phoenix (Figs. 5c, S1c); however, both cities have numerous instances of non-survivable conditions for older people in direct sun according

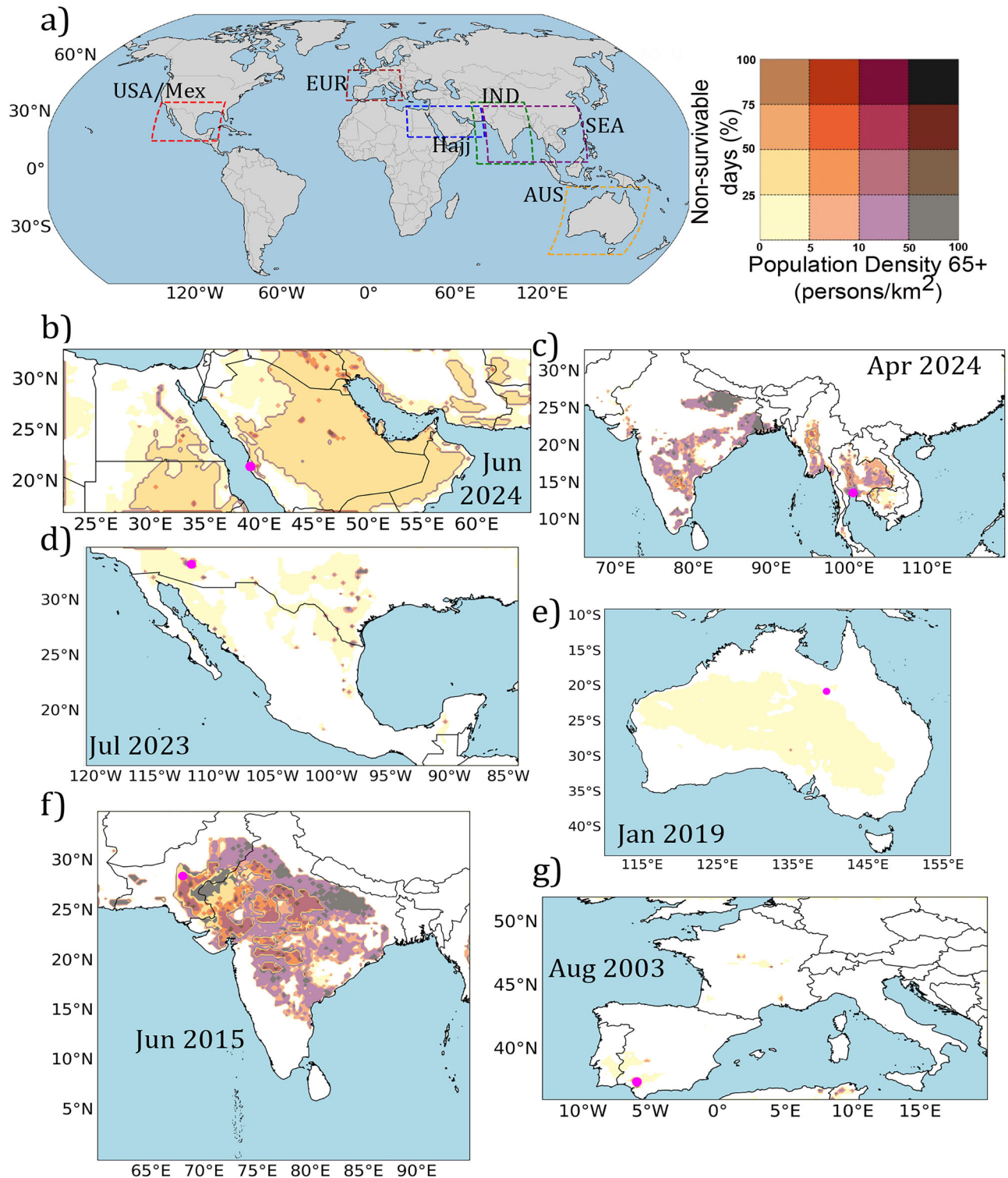


Fig. 4 | Non-survivable conditions for older people seeking shade. The proportion of non-survivable conditions during historical and extreme heat waves for older people (65+ years) seeking shade computed from ERA5, combined with estimated population density for the same age group computed from WorldPop; **a** the location of each historical event analysed; **b** the Middle East heat wave during June 2024; **c** the South Asian heatwave of April 2024; **d** the North and Central American heat wave during July 2023; **e** the Australian heatwave during January 2019; **f** the Indian heatwave during June 2015; and **g** the European heatwave during August 2003. Yellow indicates combined low population (< 5 persons/km²) and

proportion of non-survivable days (< 25%), whereas black indicates combined high population (50–100 persons/km²) and proportion of non-survivable days (> 75%). All other colours indicate a progressive and increasing combination of the two variables, reaching darker shades when variable values increase. The location of each city examined in greater detail for the observed event and future projections is indicated by the magenta dot. For specific details of each event, its location, and corresponding city, please see “Methods” and Table 1 in the Supplementary Information. Please see “Methods” for details regarding ERA5 WorldPop and non-survivability calculation.

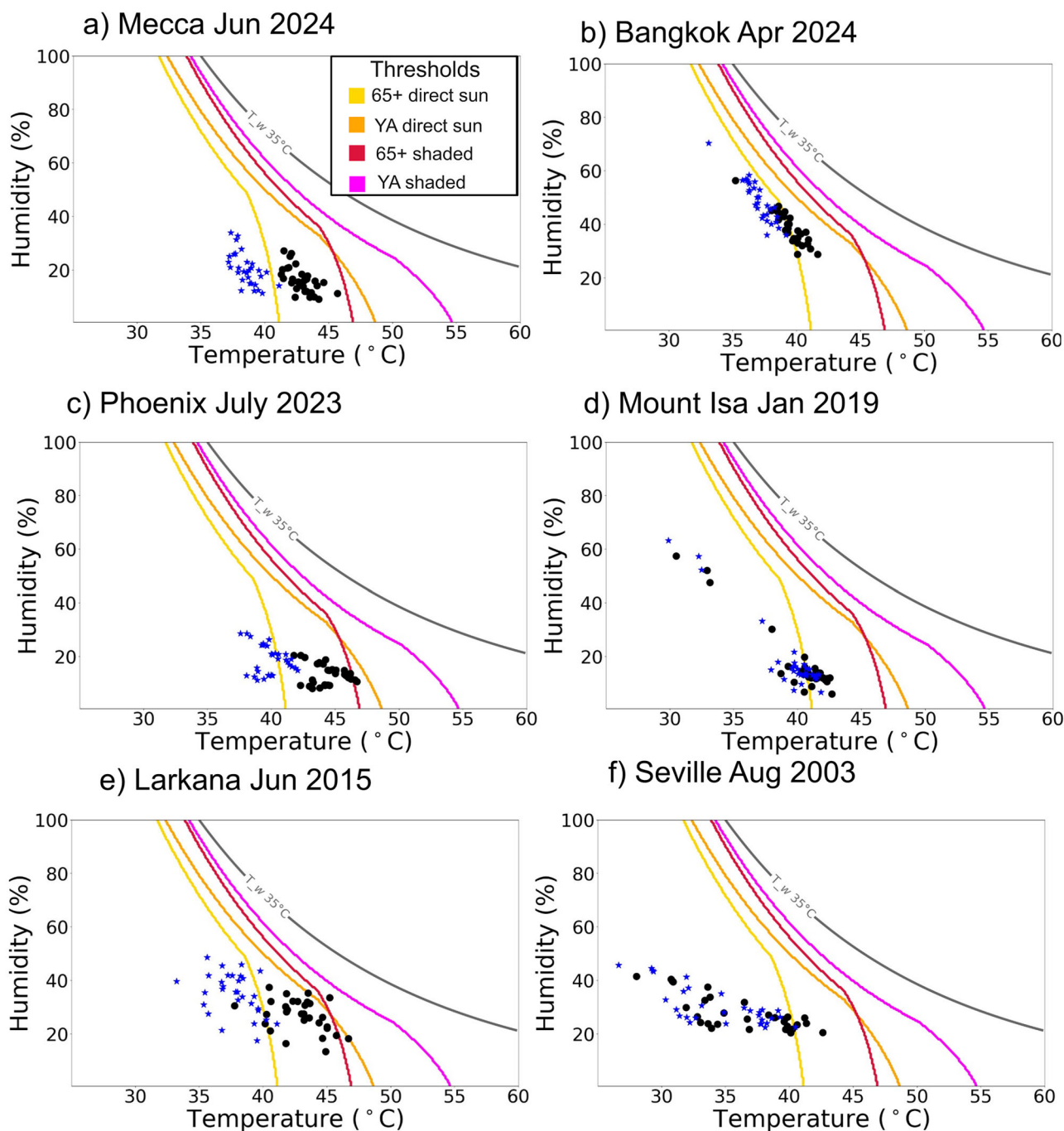


Fig. 5 | Peak six-hourly combinations of temperature and relative humidity during the day (6am–6pm local time) and night (6pm–6am local time). Each nighttime (blue star) and daytime (black dot) value is extracted from all rolling 6-hourly periods computed from 1-hourly data that fall within each time window, extracted from ERA5 for six historical heatwaves over affected cities (see Table 1); **a** Mecca during June 2024; **b** Bangkok during April 2024; **c** Phoenix during July 2023; **d** Mount Isa during January 2019; **e** Karachi during May and June 2015; **f** Seville during August 2003. Each plot also depicts the physiologically-derived non-survivable thresholds for older people in direct sun (yellow), younger people in direct sun (orange), older people seeking shade (red), and younger people seeking shade (purple), as well as the wet-bulb threshold of 35 °C. Should the purple line be crossed by a given black star or blue dot, the associated conditions during that 6-h window are non-survivable for all people, whether they are seeking shade or fully exposed. Also note that the threshold for all non-survivable conditions at nighttime follows the corresponding shade-based threshold due to the absence of direct sunlight. For more details on ERA5 and the computation of physiological heat stress thresholds, please see “Methods”. For more details on the respective historical events, please see Table 1.

sun (orange), older people seeking shade (red), and younger people seeking shade (purple), as well as the wet-bulb threshold of 35 °C. Should the purple line be crossed by a given black star or blue dot, the associated conditions during that 6-h window are non-survivable for all people, whether they are seeking shade or fully exposed. Also note that the threshold for all non-survivable conditions at nighttime follows the corresponding shade-based threshold due to the absence of direct sunlight. For more details on ERA5 and the computation of physiological heat stress thresholds, please see “Methods”. For more details on the respective historical events, please see Table 1.

to ERA5. It is important to again emphasise that even extremely hot yet very dry conditions can exceed physiological limits of survivability, which are conditions not recognised by the theoretically-based T_w 35 °C. This fact is especially evident over Phoenix (Figs. 3c, 5c, S1c), where the vast majority of non-survivable periods occur at high temperatures yet relative humidity levels at or below 20%. Furthermore,

while the local climate strongly influences how heat stress is apportioned by temperature and humidity, ascribing deadly conditions based on temperature alone likely underestimates the risk profile over humid locations³⁷, since humidity inhibits the human body’s primary cooling mechanism (evaporation of sweat). Accordingly, different temperatures can be considered either survivable or non-survivable,

based on the humidity levels. For example, temperatures of 39 °C in Bangkok on the 23rd and 24th April 2024 (Fig. 5b), accompanied by a relative humidity of ~50% (Fig. 3b), were non-survivable for the older population in direct sun, whereas 39 °C on the 17th April fell just shy of the respective non-survivable threshold as relative humidity was closer to 40%. While unlikely to cause heat stroke, the latter conditions could still have been physiologically stressful on older people in direct sunlight. Knowing the apportionment of temperature and humidity can help inform adaptation strategies to reduce exposure. There are viable and low-cost options that increase comfort during high humidity that may not be as optimal when the air temperature is instead extremely high, such as the humble fan^{75,79}.

Across all city-scale events assessed, no six-hourly period exceeded, or even came close to, T_w 35 °C. Deadly heat stress events are occurring under conditions and during a time period that was originally considered to be near impossible⁴³, and in some locations, when humidity is very low. The incorporation of human physiology into heat stress limits explains heat-related death tolls better than the T_w 35 °C threshold could. Our results underscore the vulnerability of humans to extreme conditions that will become all the more frequent as global warming continues.

Discussion

By employing physiologically relevant heat stress survivability thresholds³⁹ from HEAT-Lim, our study determined that sustained non-survivable heat stress conditions have already occurred during severe recent heatwaves. While previous research suggested a single dangerous T_w threshold⁴³, our study employs upper T_w limits that become lower with increasing ambient temperature due to physiological restrictions to maximal sweat production^{38,39}. While similar to the T_w 35 °C threshold at high temperature and humidity, differences become progressively greater at high temperatures with low humidity (Fig. 1), and even greater when accounting for solar radiation and age. Thus, the thresholds employed here are markedly lower than the original theorised survivability limit of 35 °C, especially for low humidity conditions, and were used to assess the overall heat stress exposure of different personal vulnerability profiles during six historical heatwave case studies.

We find that older people in direct sun were repeatedly exposed to deadly conditions across all events, older people in shade were briefly exposed during Phoenix 2023 and Larkana 2015, and younger people in direct sun were also exposed towards the end of the latter event. Indeed, local populations were exposed most or all days during Mecca 2024, Phoenix 2023 and Larkana 2015, events that were associated with very high reported mortality rates^{15–18} (See Table 1). Moreover, our analysis of Phoenix 2023 and Mecca 2024 reveals the danger of extremely high temperatures even when the associated humidity is very low. By employing the HEAT-Lim survivability model by Vanos et al.³⁹, we demonstrate the event-specific temperature and humidity combinations that likely instigated deaths and when they occurred and provide physiologically-based evidence that older people were indeed at far greater risk.

While the 2003 European heatwave was the region's hottest at the time of occurrence, multiple events since have set more recent climatological records⁷¹, but are systematically associated with lower mortality rates¹¹ due to enhanced preparedness and adaptations. Indeed, the 2003 European heatwave caught the region unaware, with little knowledge or mechanisms to mitigate against the adverse impacts of prolonged and extreme heat. Since 2003, considerable developments in local public education, early warning systems, and accessible mitigation strategies have considerably reduced death tolls^{70,80} despite larger potential exposure due to enhanced climatological and meteorological factors, a lesson that bodes well for future adaptation against extreme heat events.

Given the exceptional conditions across the Middle East, India/Pakistan, and South Asia events, we provide physiological evidence

that the true mortality rate was very likely much higher than reported. We make clear that HEAT-Lim only accounts for physiologically-based heat stroke mortalities, therefore not including accidental deaths, those related to poor mental health, or other excess mortality occurrences associated with the extreme conditions (e.g., cardiovascular and respiratory). Moreover, the physiological model gives information on the exposure to potentially lethal conditions rather than certain mortality. That is, if a given individual is able to access shade and/or appropriate cooling mechanisms during deadly heat stress conditions, their likelihood of perishing reduces considerably, as Fig. 3 strongly indicates. However, taking into account high population densities (Figs. 2, 4), notably reduced access to effective cooling strategies^{15–19}, lack of resources to accurately record heat stress-related mortality^{15–17}, and/or important local cultural celebrations that result in a temporary large influx of people^{18,19}, the total mortalities reported in Table 1 may severely underrepresent the true mortality signal of these extraordinary historical heatwaves. Due to the underreporting of heat-related mortality, such a hypothesis is very difficult to test, but could be an important investigation in future research. We emphasise that the non-survivable environmental conditions and the resulting mortalities are preventable with adequate infrastructure, accessible public education, and early warning systems, but many people in these regions lack access to these critical adaptations. Without adaptation, higher numbers of heat stress-associated deaths are not only observed, but will continue to increase with a warmer climate⁸¹, with underreporting of mortality also likely to propagate into the future.

Additionally, while substantial epidemiological research has formulated links between elevated temperatures and mortality^{30–37}, we demonstrate that different local combinations of heat and humidity have resulted in similar heat stress conditions. In tropical regions, heat stress limits occur at lower temperatures when relative humidity is higher (yet still nowhere near a threshold of T_w 35 °C). Such important information is likely missed when assessing heat stroke risk based on ambient temperature alone³⁷. Moreover, our analysis is based on sustained conditions over a six-hour period, enough time for overheating to instigate non-reversible physiological changes resulting in multiple organ failure and death^{24,37}. Sustained exposure to such physiological limits initiates a chain of events that is almost impossible to reverse once begun, even when expert medical care and resources are available⁶⁶. Therefore, adaptation initiatives against extreme heat and humidity are very likely to be most effective in the lead-up to an extreme event (e.g., increased access to shade, green cities, cooling considerations in building design, community cohesion)^{82–84} and for its duration (e.g., appropriate use of fans, and interventions such as skin wetting)^{75,76,79} to reduce overall exposure, thereby also reducing strain on finite medical infrastructure.

We emphasise that the environmental limits for human survivability due to heat stress³⁹ employed in the present analysis represent a conservative interpretation of heat stress risk. Recent research by other physiologists has confirmed that T_w values at which humans transition into an uncompensable heat stress state, whereby core temperature can no longer be held at a steady, unchanging level, are much lower than 35 °C^{51,85}. However, this threshold definition does not allow the core temperature to rise to hyperthermic levels, and our group has chosen to use this as a characterisation of “liveability”³⁹. It is known that some humans can safely elevate their core temperature to ~39 °C or even 40 °C often without any ill effects⁸⁶. Our approach permits core temperature to rise and defines the critical temperature and humidity thresholds as those under which core temperature increases within a 6-h exposure window to 43 °C, which could be highly likely to result in heat stroke death⁸⁷. Future studies could attempt to use full thermoregulation models to explore more dynamic responses of the human body over time, yet the computational needs and complexity are important considerations when bridging the thermoregulation models with large amounts of climate data^{88–90}.

In summary, via the application of the contemporary physiology-derived HEAT-Lim, this study provides clear evidence that sustained periods of non-survivable heat stress have already occurred during recent events across multiple regions. Such occurrences have occurred well below the originally theorised fundamental limit of T_w 35 °C and have mainly affected older people in full sun exposure of adverse ambient conditions for at least six hours. Indeed, by comparing exposed (outdoor) and shaded (closer to indoor) limits, we demonstrate that simple adaptation strategies such as seeking shade can drastically reduce heat stress risk, at least under current climate conditions. While reaching human heat stress limits was once thought impossible at the current level of global warming, brief occurrences close to the originally theorised T_w 35 °C threshold have recently been recorded⁶⁴. Our analysis provides the next crucial step in contemporary knowledge on the emergence of deadly heat stress by applying physiologically-determined thresholds to observed climate data. We demonstrate that deadly conditions have already placed hundreds of millions of people at grave risk, in both humid and dry climates, especially older people with no access to shade, and provide a physiological basis for the deadly ambient conditions that underpinned corresponding epidemiological assessments^{11–17,20,24,30–36}. In facilitating further breakthroughs in this space, future research could focus on projections of physiologically relevant heat stress conditions, disentangling the dynamics of such conditions across time, greater accuracy in the simulation of the most extreme and deadly events, and understanding the interactions of local-scale urban effects in both amplifying and mitigating against future non-survivable conditions. For this progress to successfully occur, it must be underpinned by consistent interdisciplinary collaboration, as well as understanding the nuances of specific cultural behaviours that influence an individual's exposure to the adverse effects of extreme heat.

Methods

Historical Data

The analysis of six historical heatwaves is underpinned by the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5)⁹¹. ERA5 is a high-resolution global reanalysis dataset that outputs hourly data at a 31 km horizontal resolution. The variables used were six-hourly averaged temperature and dewpoint temperature. These variables were used to calculate relative humidity using the equation:

$$RH = (e/es) \times 100$$

$$(1) \text{ Where } e \text{ (vapour pressure)} = 6.112 \times \exp((17.67 \times T_d) / (243.04 + T_d));$$

and

$$(2) \text{ es (saturation vapour pressure)} = 6.112 \times \exp((17.67 \times T) / (243.04 + T))$$

ERA5 integrates observational data with the ECMWF Integrated Forecasting System weather model to create a comprehensive and consistent climate record, making it widely used for weather and climate research, historical analysis, and model validation. It provides a distinct advantage over in-situ and gridded observational products since it is consistent in space and time from 1940 to the present. Most recent years generally consist of more observations; for example, around 24 million observations per day were incorporated by 2019, a notable increase from 0.75 million per day in 1979. From 1979–2019, about one billion surface observations were used for each of temperature and relative humidity. Observations assimilated by ERA5 are recorded by over 200 satellite instruments and many types of conventional datasets. For specific details regarding the historical heatwaves assessed using ERA5, please see Table 1.

City and station analysis

As part of our analysis, we investigate the daytime and nighttime maximum 6-hourly mean temperature and associated humidity, as well as the time evolution of each heatwave within a city affected by the

Table 2 | Co-ordinates for in-situ observations used as a comparison against reanalysis data

Station	Latitude	Longitude
Mecca	21.41°N	39.78°E
Bangkok	13.73°N	100.57°E
Phoenix	33.43°N	112.00°W
Mount Isa	20.73°S	139.48°E
Larkana	27.56°N	68.21°E
Seville	37.37°N	6.00°W

respective event. Cities were chosen because of their proximity to the highest temperatures and/or humidity values of the corresponding heatwave, as well as their populations, inferring high exposure in the absence of cooling strategies. Mecca, Bangkok, Phoenix, Mount Isa, Larkana and Seville were chosen to represent the heatwaves over the Middle East, Southern Asia, Central America, Australia, India/Pakistan, and Europe. For city-scale analysis in the main text, the corresponding grid box was selected from ERA5.

To complement the analysis of city-scale heatwaves from ERA5, we also analyse survivable limits based on station data from the Integrated Surface Database⁷⁰ (ISD), managed by the National Oceanic and Atmospheric Administration (NOAA). ISD is a comprehensive collection of meteorological observations collected from weather stations worldwide. The variables used were hourly temperature and relative humidity, which were analyzed in the same as the ERA5 variables (see above) and were available at nearby stations (coordinates below) for the entirety of each of the heatwaves included in this study. See Table 2 for station coordinates.

Population statistics

Data to determine the population density of people within the 65+ group were taken from the WorldPop dataset⁹². WorldPop data gives an estimate of the number of people per kilometre per year, separated by sex and five-year age groupings from 2000 to 2020. These statistics were aggregated to include both men and women, with all ages 65 and over, and coarsened using linear interpolation to match the resolution of the ERA5 data in order to consider population and heat stress thresholds at the same resolution. Population density was also weighted by the latitudinal cosine to ensure correct density spread. Estimates of population densities past 2020 are not available, and so the 2020 estimates were used for the more recent years.

Calculation of wet-bulb temperature

Wet-bulb temperature (T_w) was calculated using the Davies-Jones method⁹³, based on temperature and relative humidity values. T_w was computed for all six hourly ERA5 data per region and events in Table 1.

Computing physiological non-survivable heat stress limits

The survivability limits -- determined by the possibility of death as a result of heat stroke using a whole-body human heat exchange model -- were calculated from the physiological-based HEAT-Lim model (Human/Environmental Adaptation and Threshold Limits Model) proposed by Vanos et al³⁹, with the corresponding code freely available in Guzman-Echavarria and Vanos⁹⁴. This model estimates whether or not a human will survive during extreme heat exposure by calculating core temperature increases under constant thermal exposure. It assumes a person can store up to 17.88 kJ/kg of heat before reaching a critical core body temperature of 43 °C, the threshold for fatal heat stroke. The model assesses heat storage rates depending on 3- and 6-h exposures at resting metabolic rate and no clothing, matching past survivability assumptions.

HEAT-Lim accounts for three key restrictions to heat loss: environmental humidity, the skin's ability to evaporate sweat, and

maximum sweat production. Based on these factors, the model determines if an individual can survive the heat exposure, and if not, for what reason(s), by combining the environmental and physiological conditions. The model currently can be run for an average older (or more vulnerable) group (ages 65+) and an average younger adult group (ages 18–40). The main physiological differences incorporated across these profiles are lower sweat rate and the ability to wet the skin (and thus cool via evaporation) in the older age group. If able to seek shade, the mean radiant temperature (MRT) is assumed to equal the ambient temperature; however, if sun-exposed, the MRT is +15 °C above the ambient temperature as an average daytime estimate⁹⁵. The MRT is then incorporated with the restrictions surrounding heat loss as described above. Please see Vanos et al 2023³⁹ and Guzman-Echavarría & Vanos 2023⁹⁴ for specific details and formulae for HEAT-Lim. Figure 3 displays all four heat stress thresholds in each panel, as well as the original T_w 35 °C threshold. Note that the physiologically-based thresholds are not a constant T_w value. For older people in direct sun and seeking shade, respective dry bulb temperatures of above 40 °C are largely deadly regardless of humidity; however, for younger people, dry bulb temperature dominates physiological heat stress at high temperatures, about 45 °C and 50 °C, respectively. Moreover, physiological limits during nighttime follow shade-based thresholds, as there is no influence from the sun. Although ambient shade-based conditions are likely not identical to temperature and humidity values indoors, they provide a closer comparison to the thresholds that need to be exceeded for heat stroke to occur indoors than the thresholds for full exposure, especially for dwellings with natural cross-ventilation and high thermal mass.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

No new data were created or generated in this study. All data analysed are publicly available from online repositories. The reanalysis data used for heatwave analysis are available from the ERA5 dataset via the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/>). The station-based meteorological data are available from the NOAA Integrated Surface Database (<https://www.ncdc.noaa.gov/products/land-based-station/integrated-surface-database>). Population density data are available from the WorldPop dataset (<https://hub.worldpop.org/>).

Code availability

The code used to generate the results and figures in this study is available at <https://github.com/CatherineGregory/Heatwaves>.

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Author contributions

All authors conceived the study. S.E.P.-K. led the research and manuscript writing, with regular input from O.J., C.H.G., J.W.B., J.V., H.S. and G.G.-E. C.H.G. performed the technical analyses. All authors contributed to writing and reviewing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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