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Review article

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Mortality impacts of the most extreme heat events

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Abstract

Extreme heat threatens human life, evidenced by >260,000 heat-related fatalities collectively in the deadliest events since 2000. In this Review, we link physical climate science with heat mortality risk, including crossings of uncompensable thresholds (beyond which human core body temperature rises uncontrollably) and unsurvivable thresholds (lethal core temperature increase within 6 h). Uncompensable thresholds (wet-bulb temperatures ~19–32 °C) depend strongly on age and the combination of air temperature and relative humidity. These thresholds have been breached rarely for younger adults (~2.2% of land area over 1994–2023) but more widely for older adults (~21%). Unsurvivable thresholds (wet-bulb temperatures ~20–34 °C) were only exceeded for older adults (~1.8% of land area). Anthropogenic warming will lead to more frequent threshold crossings, including tripling of the uncompensable land area for young adults if warming reaches 2 °C above preindustrial levels. Interdisciplinary work must improve the understanding of the deadly potential of unprecedented heat and how it can be reduced. Ensuring reliable access for all to cool refugia is an urgent priority as the atmosphere threatens to increasingly overwhelm human physiology under climate warming.

Sections

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Introduction

Anthropogenic forcing is causing long-term heat accumulation in the ocean, land and atmosphere[1,2]. This atmospheric heat gain is manifesting most directly as an increase in the tropospheric dry-bulb air temperature (Ta). Indeed, such dry heat (the sensible term in the heat budget; Box 1) has warmed >1 °C since the preindustrial period[3]. However, climate warming also demands consideration of changes to total heat ('moist enthalpy' or 'humid heat'), not just Ta. Since 1950, around one-third of the increase in moist enthalpy – the sum of sensible and latent heat – was attributable to rising latent heat content from increasing atmospheric water vapour[4] (Box 1). Critically, these upward trends in the mean state of the climate have been accompanied by increases in the frequency and magnitude of dry and humid heat extremes worldwide[5].

These extreme heat events (dry and humid) have major and far-reaching implications for human life. Human impacts can cascade in response to those within the biosphere (for example, on crops)[6], arise from damage to thermally sensitive infrastructure[7], or result directly from physiological vulnerability to heat stress[8] (Box 2). The latter can manifest in a range of negative health outcomes[4], including death[9]. This lethal potential has been demonstrated by various mass mortality events. For instance, the three deadliest heat events of the twenty-first century collectively caused nearly 200,000 deaths[10–12], including ~72,000 across Europe during 2003, another 62,000 across Europe in 2022, and the ~56,000 killed during the Russian heatwave of 2010 (Table 1).

The projected increase in extreme temperatures is, therefore, a fundamental concern for human health[13–16]. Indeed, it is anticipated that, relative to the year 2000, 1-in-100-year heat mortality events were already 5–10 times more common worldwide in 2020, and they could occur every few years if global mean temperatures reach 2 °C above preindustrial levels[17]. However, even these projections might be conservative, as future warming could cause human physiological thresholds in heat tolerance to be overwhelmed at unprecedented scales[18–20]. Anticipating the magnitude of future heat extremes and their worst-case impacts is critical to understand the costs of failure in climate change mitigation and to target adaptation efforts at those communities most in need with appropriate solutions at the required scale.

In this Review, we summarize the mortality threat from extreme (sensible and total) heat under climate warming. We begin by outlining the physical science of extreme heat, including extreme-event drivers, climatologies and maximum possible values. We next consider heat mortality, discussing the empirical and statistical methods used to understand the evolving risk, before taking a physiological perspective to explore upper limits in human heat tolerance, including their exceedance under past and possible future climates. We subsequently address the potential of adaptation to limit mortality from future extreme heat events before closing with a summary and future perspectives. Hereafter, 'dry heat' refers to sensible heat components (proportional to Ta) and 'humid heat' to the sum of sensible and latent components (proportional to moist enthalpy and Tw; Box 1); 'heat' is used as an umbrella term for both.

The physical science of extreme heat

Before assessing the impacts of heat on mortality, it is important to consider the physical processes which explain the distributions of observed heat extremes and their sensitivity to climate warming, offering insight into their upper limits.

Drivers of extreme heat

Atmospheric dynamics are a key factor driving extreme dry heat. Such heat extremes are often linked to high-pressure systems (anticyclones), specifically adiabatic warming from descending air, reduced cloud cover and decreased precipitation[21]. These effects can be amplified in space and time if the high pressure is blocked in place[22,23]. Accordingly, anticyclonic intensification of dry heat is regionally variable, being strongest in the midlatitude regions where atmospheric dynamics enable such blocking[24]. Examples of strong anticyclonic driven heatwaves include the European event of 2003 (ref. 25) and the Western North America event of 2021 (ref. 26).

Other atmospheric and land surface factors are also implicated in extreme dry heat. For example, advection of warmer air (as in some coastal midlatitude regions such as the British Isles) and wind-driven descent of air near mountainous terrain (as in north of the Tibetan Plateau and along the Rocky Mountains), are critical aspects driving extreme Ta[27]. Surface conditions, such as low soil moisture, can also increase diabatic heating to amplify Ta by partitioning a larger fraction of net radiation to sensible rather than latent heat[28,29]. Similarly, land cover factors – including albedo, surface roughness[30], moisture availability[31], thermal properties[32] and plant hydraulics[33] – also have bearing. Urbanization, for example, can intensify Ta relative to rural areas through these surface characteristics[34], although anthropogenic aerosols can moderate these effects[35].

Like for dry heat, atmospheric dynamics also have an essential role in driving humid heat, but the modulating processes depend on the background climate. For instance, moist, energy-limited areas (such as Bangladesh) require high-pressure conditions to elevate Ta, whereas dry, moisture-limited regions (such as Pakistan) rely on moisture advection to increase atmospheric humidity[36–38]. Spatially, the most intense humid heat events are typically found collocated with surface moisture sources (which can include vegetation[39]) or closely downwind of them[37]. Accordingly, irrigation – which increases surface moisture fluxes and reduces boundary-layer depth – tends to amplify humid heat extremes in some regions, including in the central-northern US Great Plains and in the Indo-Gangetic Plain[40–44]. By contrast, urbanization tends to decrease local humidity to cause a net reduction in humid heat in some regions[45,46].

Large-scale modes of variability and remote drivers also modulate extremes in dry and humid heat. The El Niño Southern Oscillation and Madden–Julian Oscillation, for example, can influence air temperature and humidity through controls on atmospheric circulation and the surface energy balance[47–50]. Their impact on sea surface temperatures also indirectly controls the magnitude of extreme heat events. For example, the probability of humid heat extremes over tropical land increases as ocean surface temperatures climb during El Niño events[51]. Additionally, stationary wave trains can trigger simultaneous extreme heat events in multiple locations across the globe[52]. There is also a growing awareness that other hydroclimatic hazards can influence extreme heat remotely, such as the subsidence-related radiative heating on the periphery of tropical cyclones[53], the sensible heat advection caused by upwind droughts[54], or the moisture advection and re-evaporation related to atmospheric rivers or mesoscale convective systems[55,56].

Climatologies of extreme heat

Maximum observed dry heat exhibits substantial geographic variability. In the ERA5 dataset (ref. 57), the highest dry heat values are observed in subtropical, low-elevation desert regions, including the Sahara, the Middle East, South Asia, the Southwest USA and central

Box 1 | Defining heat and heat-related terms

Formally, heat is a type of energy transferred between systems[217]. Informally, however, it describes a property that the atmosphere possesses. The appropriate term for this possession is, instead, the enthalpy (H), which depends on the internal energy of the air (U) and the pressure (p)–volume (V) product:

$$H = U + pV \quad (1)$$

U is proportional to the dry-bulb temperature (Ta) of the air, with the specific heat at constant volume (c_v) being the constant of proportionality:

$$U = c_v \mathrm{Ta} \quad (2)$$

Under isobaric conditions, heat transferred to a parcel of air raises U and performs work by increasing V. This increase in H can be evaluated from Ta using the specific heat of air at constant pressure (c_p):

$$\Delta H = c_p \Delta \mathrm{Ta} \quad (3)$$

Substituting the actual temperature in Kelvin into equation (3) yields the change in enthalpy relative to absolute zero, often referred to as the sensible heat content[4,37].

The energy associated with water phase changes can be added to the sensible heat content to define the moist enthalpy (E). For an air–vapour mix:

$$E = c_p \mathrm{Ta} + L_v q \quad (4)$$

where L_v is the latent heat of vaporization and q is the specific humidity, collectively describing latent heat content[4,37].

E divided by c_p is the equivalent temperature, monotonically (but nonlinearly) related to the wet-bulb temperature (Tw)[4] — the temperature of an air parcel cooled to saturation at constant pressure by evaporation of water into it, with the increase in latent heat content supplied by the sensible term.

Adding geopotential to E provides the moist static energy, which is conserved under moist adiabatic motion and highly relevant for understanding physical processes[4,218], not least dynamical constraints on upper temperature limits[71,76].

Moist enthalpy (or humid heat or Tw) and Ta provide a bridge between fundamental atmospheric processes and critical societal impacts from heat stress. Hence, they are used throughout this Review instead of empirical metrics of human heat stress, which can be sensitive to additional factors (wind speeds and radiative environments) and are less clearly related to the heat content of the atmosphere.

Australia (Fig. 1a). Here, values reach above ~46 °C (or >325 kJ kg^{-1} for sensible heat) from adiabatic and diabatic heating[27]. Given the persistence of large-scale anticyclonic circulation, many of these regions are consistently hot for several months, with the highest Ta rising relatively modestly above the warm-season mean[58]. By contrast, variability is much larger in the mid-to-high-latitude regions, where large-magnitude anomalies occur owing to extreme circulation (high 500-hPa geopotential heights), advection and land surface forcing (very dry soil moisture)[26,27,59].

The patterns of maximum observed humid heat are somewhat different from dry heat. The most extreme humid heat occurs from approximately 15–40° of the equator in both hemispheres[37], encompassing the outer tropics, subtropics and lower mid-latitude regions (Fig. 1b). Despite a relatively small portion of moist enthalpy contributed by the latent term (~10% globally, greater in low latitude regions)[4], moisture anomalies tend to be the most important ingredient for generating humid heat extremes[37,60]. Thus, peak values (>400 kJ kg^{-1}; Tw > 32°C) occur in well-defined locations with high Ta, an abundant moisture source, and a non-convecting vertical profile: swathes of subtropical coastal land and the northern South Asian interior[37,38]. Indeed, the highest humid heat ever reported occurred at weather stations in Jacobabad (Pakistan) and Ras al-Khaimah (UAE), with Tw > 35°C; even higher values are probably reached in unmonitored locations, such as near the waters of the Persian Gulf[61]. In arid inland areas, the dependence of humid heat on moisture manifests as temporal clustering around precipitation events and as sensitivity to soil moisture and to anthropogenic land surface modification activities such as irrigation[31,62].

Hotspots in dry and humid heat are generally captured well by climate models[63]. However, biases in intensity often need to be corrected[19], and important regional scale features can be missed if model resolutions are too coarse[64].

Changes in extreme heat

Heat extremes have become more intense as global mean temperature has risen[65]. Notable hotspots of increasing dry heat extremes (other than the Arctic, excluded from this Review) are Western Europe and the Amazon[66,67], where annual maximum Ta has increased more than five times faster than the global mean in the most rapidly warming regions (Fig. 1c). Trends in humid heat extremes have been more latitudinally uniform, with larger changes in sensible heat at high latitudes compensating lower increases in latent heat[4] (Fig. 1d). Humid heat trends are also similar between land and ocean, consistent with theoretical expectations and baseline climatologies[4,68]. However, some hotspots of humid heat changes are also evident, including the Arabian Peninsula where annual maximum Tw has increased up to four times faster than global mean Ta. A rising trend in the frequency of dry and humid heat has also been observed[5,69]. Collectively, exposure to extreme humid heat has increased more rapidly than exposure to dry heat, partly given the concentration of people at lower latitudes, with a highly unequal socioeconomic footprint[65].

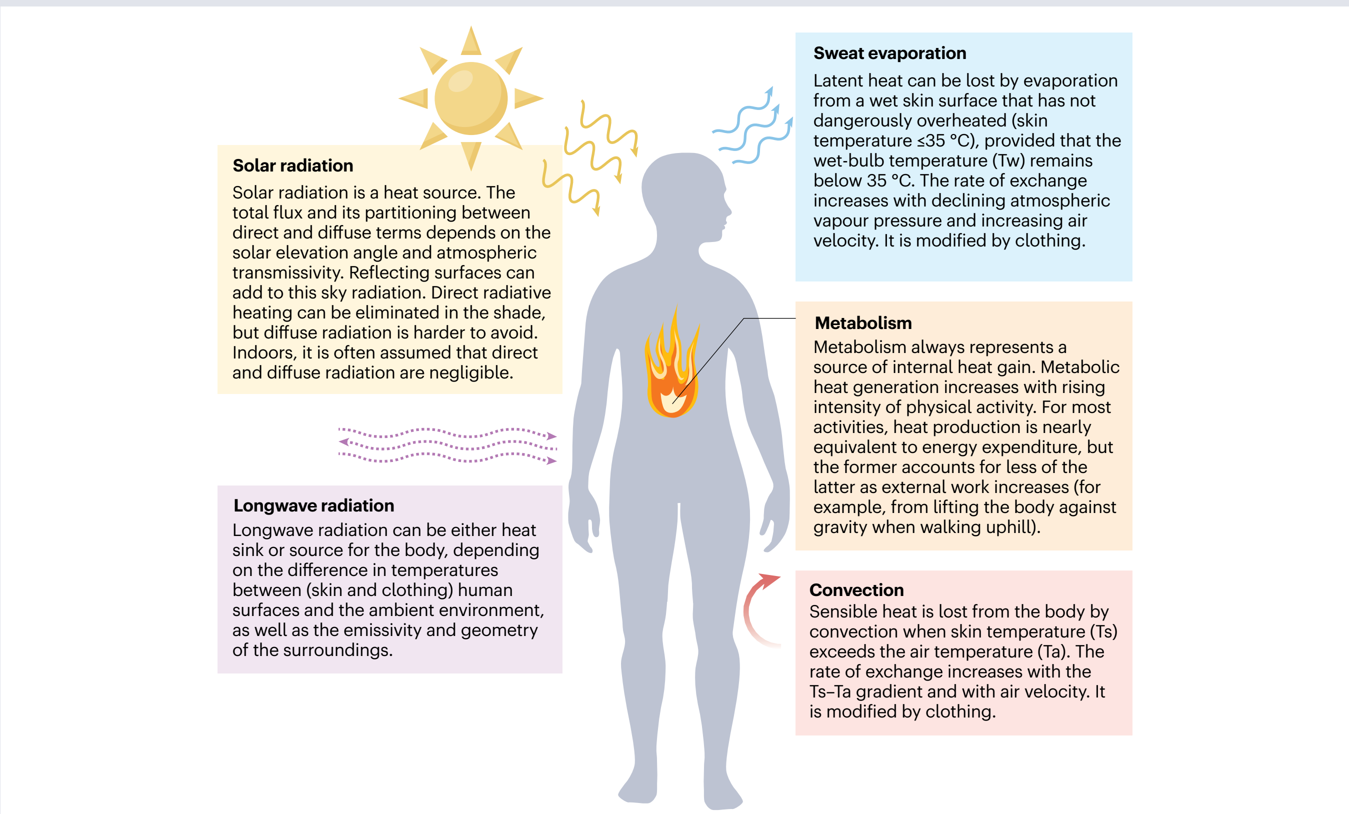
Modelling indicates that anthropogenic warming will continue to intensify extreme dry heat[70]. In CMIP6 simulations, projected changes (which are not strictly comparable in magnitude to observed trends, in part because averaging across the ensemble removes natural variability) identify patterns broadly consistent with the observed record, including agreement on the hotspots of change. For example, the largest increases in extreme dry heat are projected in Amazonia, Central Europe and Central North America, where extreme Ta could increase

Box 2 | Human heat balance and thermal physiology

The heat balance of a naked human is influenced by various processes (see the figure). Heat is exchanged between the skin and the atmosphere via sensible heat exchange (convection, scaling with gradients in dry-bulb temperature) and latent heat transfer (sweat evaporation, scaling with gradients in vapour pressure)[219]. These skin surface fluxes also scale with wind speed. Shortwave heat fluxes (solar radiation) are similarly important, consistently providing a heat source unless indoors or well shaded. Longwave radiation is a further contributing factor, with the atmosphere generally becoming less of a heat sink, and eventually a heat source, as sensible and latent heat content climb — as explained by the Stefan Boltzmann Law and the dependence of emissivity on humidity[220].

These processes can collectively contribute to heat stress if heat gain dominates. The primary physiological responses to such heat stress are increases in skin blood flow (enhancing the skin–atmosphere sensible heat gradient) and sweat rate (enhancing the skin–atmosphere latent-heat gradient), together enhancing moist enthalpy dissipation. Elevated skin blood flow also allows warm blood from the core to be cooled at the skin surface through sweat evaporation. If these responses are sufficient to arrest the climb in blood temperature, the environment is 'compensable'; toxic effects of hyperthermia should be avoided if core body temperature equilibration occurs below 42 °C and if excursions above 37 °C are brief[157,221]. However, if these physiological responses are insufficient, the environment is 'uncompensable', and if core temperature exceeds ~42 °C, direct cell damage, DNA damage, protein aggregation and loss of membrane potential can occur[152]. Although cell survival times vary based on temperature, cell type and phase of the cell cycle[222], even brief periods at such extreme levels of hyperthermia tend to be lethal.

However, human mortality attributable to extreme heat is not typically from hyperthermia[9]. In general, the myriad of pathways to heat-related death (cardiovascular, renal, endotoxemia) result from blood temperature being a high priority homeostatic variable, defended at the cost of other systems (such as fluid balance and blood flow delivery to central organs). These same pathways, even when they do not lead directly to death, are associated with heightened morbidity.



by more than 2 °C per degree of warming (Fig. 1e). Enhanced warming of extremes in these locations is explained by declines in evaporative fraction from reduced soil moisture[29,71,72], particularly on the hottest days[25,73,74]. In the tropics, this amplified increase in Ta extremes can be quantified using relative humidity (RH) conditioned on historical Ta extremes to distribute tropical moist enthalpy gains — which are controlled by tropical sea surface temperature warming[72]. At the global scale, CMIP6 projections indicate monotonic increases in the occurrence of historically rare or record setting dry heat as global mean temperature rises. For instance, the historical 99th percentile in dry heat (43.35 °C) is projected to become 2.2 times more common as the climate warms from 1 °C (the approximate amount of warming 1994–2023 since preindustrial period[75]) to 2 °C above preindustrial levels, and 7.4 times more common for 4 °C of warming since preindustrial period (Fig. 1g). Historical maximum dry heat (51.19 °C) is projected to become ~50 and 5,000 times more common at 2 °C and 4 °C above preindustrial levels, respectively, relative to its frequency at 1 °C above preindustrial levels (Fig. 1h).

Projected changes in humid heat also broadly mimic the patterns from observations. Tw extremes in the northern extratropics are anticipated to rise faster than global mean Ta, whereas the scaling is generally less than unity elsewhere. In the tropics, the increase in extreme Tw per degree of anthropogenic warming corresponds more closely with the slightly lower tropical mean Ta warming rate[76] (Fig. 1f). However, a tropical hotspot of change is found in Amazonia, where Tw is projected to increase faster than global mean Ta. In agreement with the observed changes, similar hotspots of extreme low-latitude Tw warming are in subtropical North Africa and across the Arabian Peninsula into Western Asia. These locations all share an expectation for an increased advection of water vapour under future climate scenarios[77,78]. In Amazonia, projected enhancement of downwelling solar radiation could additionally increase humid heat accumulation[37,79,80]. In contrast to dry heat, the frequency of extreme humid heat exhibits stronger nonlinearity as the climate warms, with historical humid heat extremes (Tw 99.9th percentile; 27.62 °C) projected to become 3.7 times and 27 times more common for warming of 2 °C and 4 °C, respectively, relative to 1 °C above preindustrial levels (Fig. 1g). The equivalent projected change for historically record-setting Tw (34.64 °C) is ~120 and 6,900 times greater frequency as the climate warms to 2 °C and 4 °C above preindustrial levels, respectively (Fig. 1h).

Thus, dry and humid heat extremes are projected to continue rising with global mean warming, broadly in alignment with the general patterns already observed. Most of these increases are attributable to changes in the energy balance of the atmosphere, with trends in circulation having a secondary role[58,63,81,82]. Temperature and moisture probability distributions also generally shift upward with little change in shape[65,83–85]. Changes in moisture are critical in explaining global hotspots of increasing dry and humid heat extremes, but they are also subject to large uncertainties. In particular, processes which control surface moisture fluxes are underrepresented in models, including from human actions (such as irrigation[86]) and from natural feedbacks (for instance, between drought, wildfire and surface energy fluxes[87]).

Upper limits on extreme heat

Beyond quantifying rates of change, assessing maximum plausible dry and humid heat extremes under climate change is critical for understanding the risks of crossing key (for example, biophysical) thresholds[88,89], beyond which impacts could drastically increase. These upper bounds on Ta and Tw can be estimated statistically using suitable generalized extreme value (GEV) distributions with negative shape parameters defining the upper limit of support[20,90,91]. Large ensemble climate modelling has also emerged as key tool to explore maximum plausible values, including reducing GEV parameter uncertainty from greatly increased sample sizes[63,92]. However, even with ensemble sampling algorithms designed to generate the most extreme heat[93–95], model simulations are not guaranteed to reach

Table 1 | The deadliest heat events since 2000

Date	Region	Country-level mortality[a]	Total mortality[a]
05/2002	Asia	IND (1,030)	1,030
05/2003–06/2003	Asia	BGD (62), PAK (200), IND (1,210)	1,472
07/2003–08/2003[b]	Europe	LUX (170), ESP (15,090), SVN (289), SVK (nan), PRT (2,696), NLD (965), ITA (20,089), HRV (788), GBR (301), FRA (19,490), DEU (9,355), CZE (418), CHE (1,039), BEL (1,175), AUT (345)	72,210
06/2006–08/2006	Europe	BEL (940), DEU (2), ESP (21), FRA (1,388), NLD (1,000), PRT (41)	3,392
06/2010–08/2010	Europe	RUS (55,736)	55,736
05/2015–05/2015	Asia	IND (2,248)	2,248
06/2015–06/2015[b]	Asia	PAK (1,229)	1,229
06/2015–08/2015	Europe	BEL (410), FRA (3,275)	3,685
07/2019–07/2019	Europe	NLD (400), AUT (1), FRA (868), DEU (nan), BEL (400)	1,669
06/2020–08/2020	Europe	NLD (400), GBR (2,556), FRA (1,924), BEL (1,687)	6,567
06/2021–07/2021[b,c]	North America	CAN (815), USA (229)	1,044
05/2022–09/2022	Europe	FIN (225), HUN (513), IRL (26), ITA (18,010), GBR (3,469), FRA (4,807), HRV (731), EST (167), ESP (11,324), DNK (252), LUX (44), DEU (8,173), CZE (279), LTU (381), ROU (2,455), LVA (105), MLT (76), MNE (50), NLD (469), NOR (30), POL (763), PRT (2,212), CHE (302), SRB (574), SVK (365), SVN (154), SWE (40), CYP (101), GRC (3,092), BGR (1,277), BEL (434), AUT (419), ALB (352)	61,671
07/2023–09/2023	Europe	DEU (6,376), DNK (189), ESP (8,352), ISL (0), FIN (138), FRA (2,734), GBR (1,851), GRC (4,339), HRV (561), HUN (294), IRL (60), EST (103), LIE (1), ITA (12,743), CYP (151), LTU (247), LUX (33), LVA (58), MLT (70), MNE (41), NLD (368), NOR (29), POL (616), PRT (1,432), ROU (2,585), SRB (464), SVK (247), CZE (361), BGR (1,670), CHE (294), BEL (324), SWE (13), SVN (95), AUT (486), ALB (363)	47,688
06/2024–06/2024[d]	Asia	SAU (1,000)	1,000

nan, not a number. [a]Heat events with at least 1,000 deaths from EM-DAT[216]. [b]Events included in Fig. 2. [c]Aggregated from two separate events in EM-DAT[216]. [d]Mortality during the 2024 Hajj also discussed in the text[165].

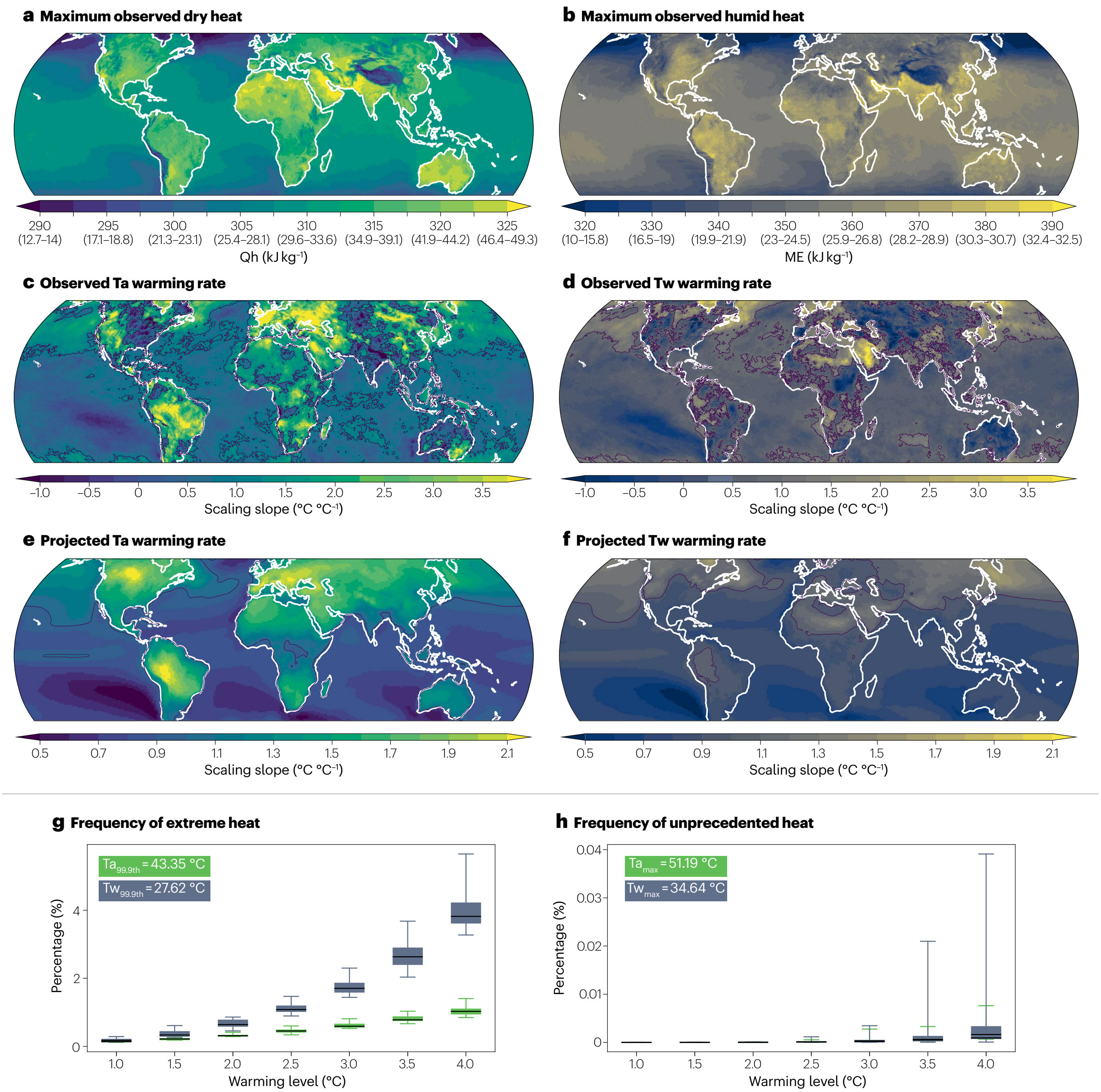


Fig. 1 | Observed and projected extreme heat. a, All-time maximum 2 m sensible heat (Qh) or empirically derived dry heat (Ta, °C, in parentheses) from ERA5 (ref. 57) over 1979–2022. **b**, As in panel **a** but for moist enthalpy (ME) or humid heat (Tw, °C, in parentheses). **c**, Observed annual maximum Ta warming rate from ERA5 over 1979–2022, derived by regressing annual maximum Ta upon global mean 2 m temperature. **d**, As in panel **c** but for annual maximum Tw. **e**, As in panel **c** but projected warming rate from 1960 to 2100 using an ensemble of 16 CMIP6 models[19]. **f**, As in panel **e** but for Tw. The black (panels **c** and **e**) and purple (panels **d** and **f**) lines denote the unity contour (a 1 °C change in the extreme value per 1 °C of global mean Ta warming). **g**, The percentage of grid-cell/hour combinations over land within 60°N–40°S where Ta (green) and Tw (grey) exceed historical thresholds (the 1979–2022 ERA5 99.9th percentile; coloured boxes) under 1–4 °C warming since preindustrial period, using the same bias-corrected CMIP6 data[19]. The box plot represents the 25th–75th percentiles of the model spread, the bold line the median, and the whiskers the ensemble maximum and minimum values. **h**, As in panel **g** but with the thresholds defined as ERA5 historical maxima. The temporal frequency of ERA5 and CMIP6 data is three-hourly for all analyses. Extreme dry and humid heat are increasing and will continue to increase in magnitude and frequency, with differences in responses explained by physical processes.

the upper limits for a given climate state[59]. Statistical fits might also be unrealistic. The identification of physical constraints on limits to extreme heat has, therefore, been a critical development, with convective thresholds — themselves related to the large-scale climate state — now recognized as a key control on maximum humid and dry heat extremes in some regions[71,76].

Maximum plausible Tw in the tropics has been assessed using this physics framework, where the tropical free atmosphere is moist adiabatic and horizontal temperature gradients are weak. These environmental conditions create a convective cap on near-surface Tw, controlled by zonal-mean moist static energy, and the extent of negative buoyancy effects from dry air entrainment within convecting plumes[96]. The strength of this cap, in turn, scales almost ~1:1 with tropical mean Ta[76], consistent with maximum tropical sea surface warming, and the greater dry-air entrainment from increasing tropospheric dryness (relative to saturation) as the climate warms[76,96]. This scaling provides a convenient framework to assess the potential for extreme Tw to exceed critical physiological thresholds in human heat tolerance under anthropogenic warming scenarios.

Maximum plausible dry heat can also be constrained using convective thresholds, subject to assumptions about the fraction of moist enthalpy apportioned to the sensible term. This physics framework can also be applied in the mid-latitude regions over land in the summer, where the assumption of a moist adiabatic atmosphere (on which the framework relies) is generally appropriate[71]. The mid-atmosphere moist static energy (which sets the upper Ta limit) at these latitudes is controlled by processes at a range of scales. Convective activity has been identified as important locally[97], although warm conveyor belts ahead of extratropical cyclones can drive long-distance transport of moist enthalpy into the mid-atmosphere[98–100]. The result, however, is a convective cap (mid-atmosphere Tw) that has scaled historically ~1:1 with global mean Ta, which means that maximum possible (near-surface) Ta has increased almost twice as fast[71], in relatively close agreement with the largest projected changes in extreme mid-latitude Ta (Fig. 1e). This physics framework also reveals that historically extreme Ta in the mid-latitude regions could have been substantially greater if land surfaces had been drier[71,101]. During 2019, for example, record-setting dry heat in Western Europe could have been over 10 °C higher in some regions, which means that 46.6 °C was plausible in Paris (France) and 50.1 °C in Frankfurt (Germany)[101]. Large climate model ensembles support this interpretation, highlighting that if interacting factors (soil moisture and circulation anomalies) optimally combine, maximum Ta anomalies across much of the Northern Hemisphere extratropics could have been ~25–50% greater than observed maxima (1979–2018), even in a preindustrial climate[59].

Hence, across much of the tropics and mid-latitude regions, upper limits on Tw and Ta can be identified. Physical considerations indicate that these limits should be expected to rise faster for Ta than for Tw[71,76]. Moreover, linear changes in maximum possible Tw under anthropogenic warming imply nonlinear increases in maximum possible Ta as the climate warms[37,71,76]. Whether climate models exhibit biases in simulating the rare interacting processes required to generate the most extreme events is not yet clear, but they support theoretical arguments on the high potential of record-shattering heat extremes with further warming[59,71,76,93,101].

The deadly impacts of extreme heat

Despite near-hairlessness, sweating capability and bipedalism contributing to heat tolerance[102–104], humans remain physiologically vulnerable to extreme heat (Box 2). Indeed, heat-related mortality is well-documented and occurs through direct pathways (related to heat stress on human physiology) or indirect pathways (including biosphere or agricultural interactions — for instance, through crop failure[105,106] or livestock mortality and production[88,107] — threatening food security and nutrition). Estimates of heat-related mortality, the upper limits to heat tolerance, the crossing uncompensable thresholds, and warming impacts on heat threshold exceedances are now discussed. Note, caution should be applied in interpreting the magnitude and ordering of deadly heatwaves discussed here owing to inconsistent methods in attributing mortality which probably underestimate deaths in the Global South[108,109].

Estimating heat-related mortality and mortality risk

Observed extreme heat events have been associated with substantial mortality, with the deadliest recorded heat episodes since the year 2000 collectively resulting in >260,000 deaths (Table 1). Furthermore, statistical models (using daily mean Ta to characterize heat and considering lagged effects of exposure[110]) suggest that ~1% of all deaths during 1990–2019 worldwide were caused by Ta above an optimum level[111], with approximately 37% of this total attributable to anthropogenic climate change[112].

Statistical modelling also indicates that extreme events contribute disproportionately to total heat mortality[111]. For instance, almost 75% of the heat-related mortality in the deadliest events on record is attributable to the three most severe episodes (Table 1). The top-ranked event (European heatwave in 2003) represents ~28% of the total mortality, with deaths concentrated in France and Italy; in Paris alone — which had the most heat deaths among French cities — 2,100–3,400 died from extreme heat[17,113]. After Europe, Asia suffers the most deaths, including two events in 2015[114] when mass heat mortality occurred separately in India (over 2,200 deaths, mostly in Andhra Pradesh and Telangana[115]) and Pakistan (Karachi, >1,200 deaths[108]). The deadliest event of North America (>1,000 deaths) experienced the highest heat mortality around Vancouver, Canada, in 2021 (354 deaths)[116]. Despite statistical expectations of relatively high mortality from extreme heat events[111], Africa is not represented in Table 1, consistent with expectations that heat mortality is chronically under-reported[109]. However, although mortality is unknown, the 2024 extreme heat event in Nigeria — with an epicentre around megacity Lagos — was reported to increase demands on health-care services[117].

Vulnerability to such heat-related mortality is strongly linked to physiological factors. Age, in particular, is a key constraint, with older adult individuals (above ~60 years old[118,119]) generally associated with higher mortality risk than younger adult individuals (~18–60 years old[119]), consistent with physiological considerations[120,121]. However, those of a very young age (under ~10 years old) have also been found to be at increased risk[122,123]. Comorbidities can similarly increase mortality risk — particularly cardiovascular and respiratory disease[9]. Although hyperventilation[124] and the direct effects of breathing hot air (including airway inflammation[125]) explain some of this increased vulnerability for those with respiratory comorbidities, the poor air quality observed during extreme heat events is an important contributor[126]. Air pollution and extreme heat can also interact synergistically to amplify mortality, as demonstrated during combined heatwave–wildfire events in Russia[127] (as in year 2010 in Table 1) and California[128].

Behavioural and socioeconomic factors additionally modulate mortality risk. For example, during the 2003 European heatwave (Table 1), lower death rates occurred among those who dressed lightly and deployed personal cooling techniques[129], factors which aid heat dissipation[130]. The capacity for such behavioural modification is shaped by socioeconomic factors, with employment requiring manual work (and, hence, extra metabolic heat generation) and social isolation (associated with low levels of mutual aid and probably inadequate deployment of personal cooling strategies[131,132]) identified as key risk factors[133]. Evidence also suggests that unavoidable exposure to extreme heat in some forms of employment (such as agricultural work) could explain some observations of mortality risk peaking in younger adults (18–34 years old), despite their lower physiological vulnerability[134]. Socioeconomic status, inequalities and discrimination have been further strongly tied to enhanced risk from heat-related mortality, whereby those in lower-income and deprived communities often lack access to cooling resources[135]; the 1995 Chicago[136,137] and 2015 Karachi[108] events provide clear examples. In Pakistan, for instance, those unable to access water and electricity were found to be at elevated risk of dying, probably because they could not follow public health advice for heat relief[108].

These vulnerabilities, along with other factors, challenge the quantification of heat mortality risk from extreme heat based on physical principles. For example, the highly variable vulnerability to extreme heat from heterogeneous physiology, behaviour and socioeconomic status makes it intractable to identify universal heat thresholds beyond which mortality risk should start to increase. These factors are compounded by uncertain estimates of exposure due to heterogeneity in thermal environments (itself related to socioeconomic factors[134,138,139]) — variability, both spatial and temporal, not captured by widely available climate datasets[140,141]. For example, differences in Ta linked to vegetation abundance caused mortality risk during the 2003 European heatwave to vary at the neighbourhood scale in Paris[129,142]. At ever finer scales, mortality risk can vary within and between residential structures, with poor thermal insulation, high solar-radiation exposure, reduced air circulation and high building floor as risk factors[136,141].

Empirical approaches drawing on high-quality, high-resolution mortality data enable the net effects of these complexities in exposure and vulnerability to be captured statistically, quantifying the spatially variable relationship between large-scale heat in gridded climate datasets and mortality[17,111,143]. Such statistical projections indicate potentially strong increases in heat mortality under climate warming, with the largest increases in heat deaths expected to occur for regions already hottest and with the highest existing burden[17,144,145]. For instance, Southeast Asia could experience over ten times more heat-related deaths than in 2010–2019 if warming reached 4–5 °C above preindustrial levels[144]. Historically rare mass heat mortality events could also become increasingly common and potentially move into unchartered territory. For example, at 2 °C above preindustrial levels, heat-related death totals in Paris equivalent to the 2003 event would be expected to occur every few years, ~27 times more often than expected in the climate of 2003. Similar increases in the frequency of 1-in-100-year mortality events could be expected in nearly all locations where data availability enables estimation (elsewhere in Europe, the Americas, southern Africa and eastern Asia)[17].

Any empirical-statistical estimates of the mortality burden must, however, be viewed in the context of their assumptions regarding the stationarity of vulnerability and exposure through time[146]. For example, beyond autonomous physiological acclimatization, humans can adapt behaviourally and technologically to reduce vulnerability and exposure to extreme heat[147]. Indeed, there is already widespread evidence that mortality sensitivity to extreme heat has declined[148,149], probably linked to overall health improvements, the implementation of heat–health warning systems, and the greater prevalence of air conditioning[149–151].

The upper limits to human heat tolerance

Conceptually, statistical modelling of future heat mortality is challenged by the need to extrapolate to warmer climates, in which physiological considerations identify the potential for a sharp upward inflection in mortality if key thresholds are breached. First, moist enthalpy cannot be dissipated to an atmosphere with higher total heat content, which means that core human body temperatures must (subject to no other means of heat exchange) rise if this limit is breached. Second, death is the inevitable consequence of unchecked core temperature increase owing to fundamental biophysical limits (for example, linked to protein denaturation[152]; Box 2). Identifying the limits in thermoregulation for humans, and the extent to which they are crossed at different warming levels, is therefore critical. Once breached, direct heat deaths could rise sharply — an inflection that might be missed by statistical projections if calibrated mainly on the indirect (mostly cardiovascular and respiratory) causes of heat mortality dominating in the past. Heat thresholds beyond which core human body temperature cannot be prevented from rising uncontrollably (the 'uncompensable' threshold) and thresholds beyond which this core temperature rise can reach an almost certainly lethal 42 °C within a specified period (the 'unsurvivable' threshold) are now explored (Supplementary Text 1). In all cases, thresholds are defined for scenarios without solar radiation—an additional heat source critical for assessments of liveability[153], but less relevant for survival situations in which it is assumed that sunlight would be avoided[18,154]. Note that the terms 'uncompensable' and 'unsurvivable' are used to describe conditions exceeding the physiological thresholds.

There are various estimates of uncompensable heat depending on age. The thermodynamic environment defining the onset of uncompensable heat for humans at rest has been approximated as Tw = 35 °C (ref. 89). This level has not yet been observed at regional scales, but it has occurred briefly at weather stations in the Middle East and Indus Valley[61]. However, physiological research using trials in environmental chambers suggest that the 35 °C wet-bulb limit is too high for levels of metabolic heat production essential for daily living. Accordingly, these investigations indicate uncompensable wet-bulb temperature thresholds of ~25–31 °C for younger adults (~18–34 years old) and 23–29 °C for older adults (above ~65 years old) for healthy North Americans performing light activity indoors[120,155]. The lower Tw thresholds in older adults reflect impaired thermoregulatory responses with ageing[18,120,156]. Physiological heat balance modelling reproduces these experimental limits well[18,157], enabling definition of critical thresholds over a wider range of Ta and RH combinations, indicating uncompensable Tw thresholds of ~22–32 °C for younger adults (18–40 years old) and 19–31 °C for older adults (>65 years old)[18] (Supplementary Text 1 and Supplementary Fig. 1). In these chamber and modelling experiments, the uncompensable Tw thresholds decline sharply with higher Ta–lower RH combinations as limits to sweat-based cooling are breached[18,155,158]. The extent to which these uncompensable thresholds apply to other populations (from regions with higher moist enthalpy or with specific chronic health conditions) is uncertain[19].

In addition to uncertainty in uncompensable thresholds themselves, there is inconsistent interpretation of the consequences from crossing them. Whereas some have assumed that 6 h at the uncompensable threshold would lead to fatal overheating[19,20], others assert that a greater 6-h intensity would be required[18,157]. For example, core body temperature could equilibrate at a slightly elevated (above 37 °C) but non-lethal (<42 °C) level for heat at (or marginally exceeding) the uncompensable threshold[157]. Accordingly, physiological

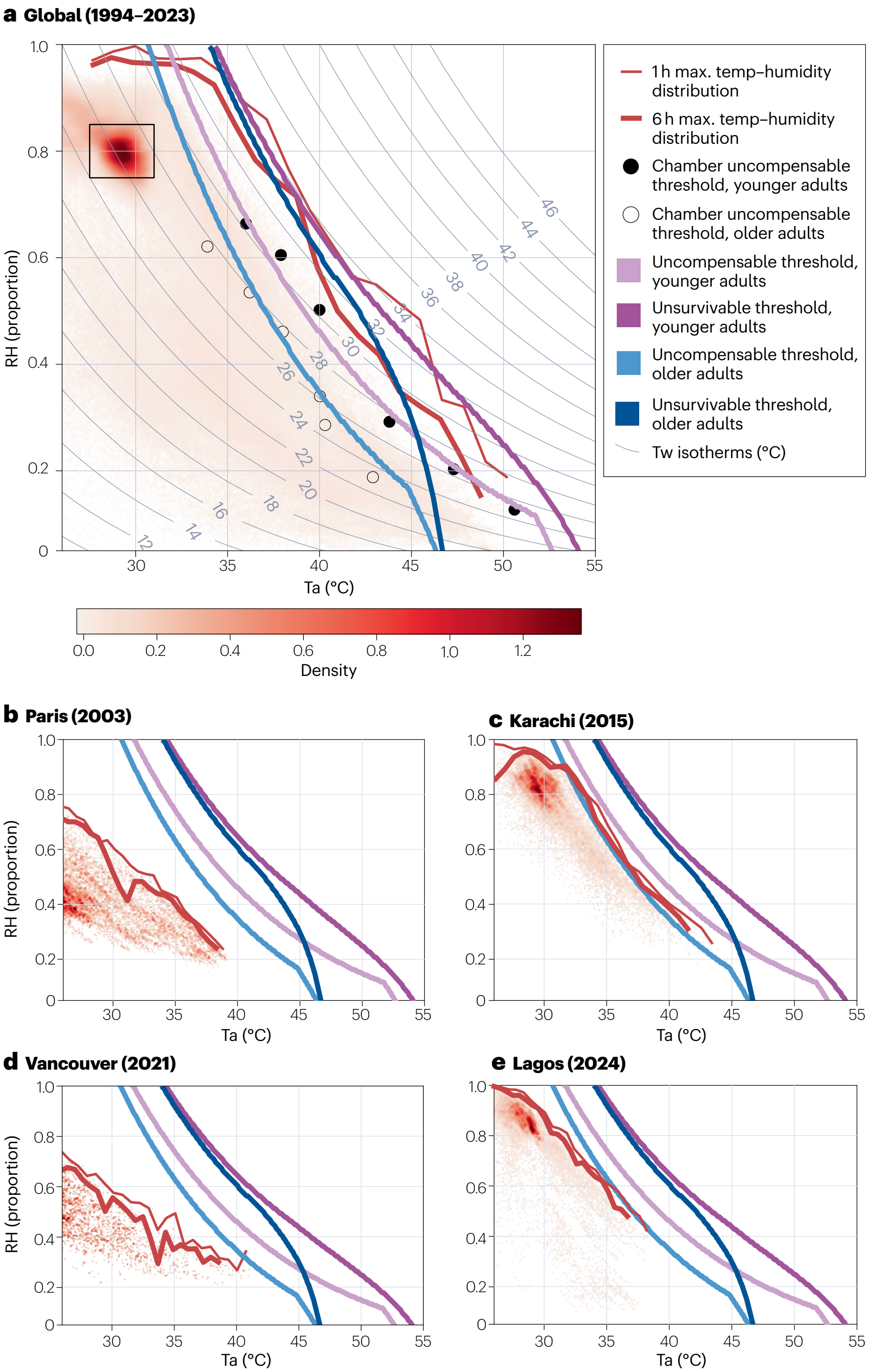


Fig. 2 | Heat and humidity during the deadliest heat events. a, The density of dry heat (Ta)–relative humidity (RH) combinations during the all-time highest hourly heat index values for each grid point over 1994–2023 in ERA5 (ref. 57). The black rectangle highlights the most frequently occurring Ta–RH combinations, corresponding to the peak heat index values over the tropical and subtropical oceans (Supplementary Fig. 3). Thin and thick red lines denote the maximum (max.) observed (or upper limit of) hourly and six-hourly humidity–temperature relationships, respectively. Uncompensable (lighter lines) and unsurvivable (darker lines) critical thresholds are from ref. 18, with the latter being appropriate for a 6-h exposure; circles indicate the corresponding uncompensable thresholds from environmental chamber analyses[120,155]. Young adults are defined here as individuals aged ~18–40 years old and older adults are those aged >65 years old; see Supplementary Text section 1 for further details. **b**, As in panel **a** but for all hours during the deadly heat event in Paris, France, in 2003 (Table 1) using ERA5 data in a 1° × 1° latitude/longitude box centred on 48.86°N, 2.35°E. **c**, As in panel **b** but for the deadly heat event in Karachi, Pakistan (24.86°N, 67°E) in 2015. **d**, As in panel **b** but for the deadly heat event in Vancouver, Canada (49.28°N, −123.12°E) in 2021. **e**, As in panel **b** but for the deadly heat event in Lagos, Nigeria (6.5°N, 3.4°E) in 2024. The most intense heat exceeds uncompensable thresholds for young and older adults and the unsurvivable threshold for older adults. The most extreme heat also approaches the unsurvivable six-hourly threshold for young adults in humid environments, and it flickers past it for individual hours.

modelling[18] – used here as a definition of unsurvivable heat – suggests a critical 6-h Tw of 23–34 °C for younger adults and ~20–34 °C for older adults (Supplementary Text 1). Uncertainty in unsurvivable heat for different exposure times is likely to remain larger than that in uncompensable thresholds because chamber experiments cannot directly investigate unsurvivable heat owing to the obvious constraint of needing to protect human life.

Crossing uncompensable thresholds

At the global scale, many extreme temperature events have breached uncompensable limits. The most extreme hourly and six-hourly heat has crossed uncompensable thresholds for younger adults (Fig. 2a, compare red lines with lighter purple line), with roughly 2.2% and 0.6% of the land surface experiencing at least 1 h or 6 h of uncompensable heat for young adults during the 1994–2023 period, respectively

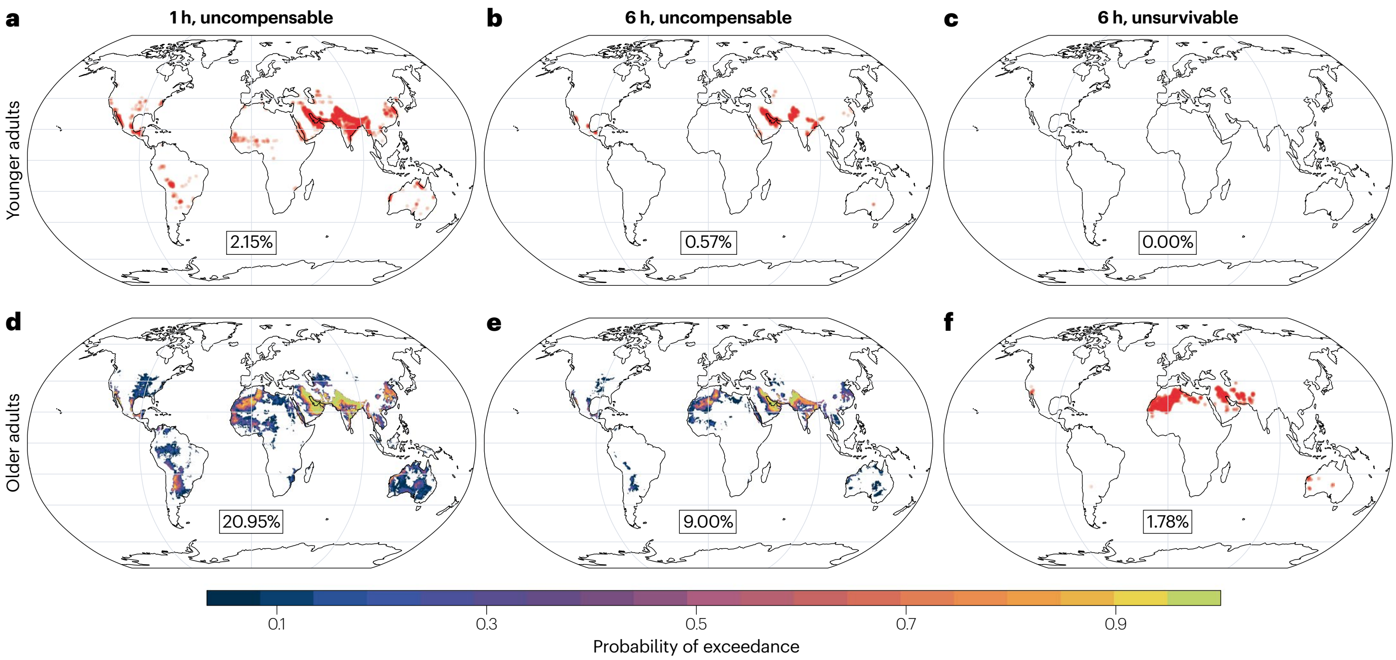


Fig. 3 | Observed crossing of uncompensable and unsurvivable thresholds. **a**, The empirical probability of the annual maximum heat index exceeding the uncompensable threshold for younger adults (18–40 years old)[18] for 1 h in ERA5 (ref. 57) over 1994–2023. **b**, As in panel **a** but for six-hourly means. **c**, As in panel **a** but for the unsurvivable threshold[18] in younger adults for 6 h. **d**, As in panel **a** but for older adults (>65 years old). **e**, As in panel **b** but for older adults. **f**, As in panel **c** but for older adults[18]. Values indicate the percentage of land surface area to have experienced at least 1 year in which the threshold was crossed; if <5%, grid cells that breach the threshold are shown in red rather than the colour bar. Uncompensable heat has occurred rarely for younger adults and more widely for older adults in the tropics and subtropics; unsurvivable heat has occurred over the hottest subtropical regions for older adults.

(Fig. 3a,b). Geographically, most of these uncompensable heat events have occurred in the Persian/Arabian Gulf region and across the Indo-Gangetic Plain, with more isolated hotspots in tropical West Africa, the Amazon Basin, the southern USA and Mexico, Australia, and eastern China. These exceedances generally align with evidence from weather stations[20,159].

Given that uncompensable thresholds are lower for older adults, these too have been crossed. The magnitude of these exceedances far outweighs those of young adults (Fig. 2a, compare red lines with lighter blue line). For instance, ~21% of the land surface experienced at least 1 h exceeding the uncompensable threshold for older adults (Fig. 3d), and ~9% of the land surface exceeded it for at least 6 h (Fig. 3e). The pattern of these exceedances largely mimics that of younger adults but is more spatially extensive.

Intuitively, unsurvivable thresholds have been crossed to a lesser degree. The most extreme hourly heat displays strong alignment with the unsurvivable threshold of young adults[18], although it has not yet been maintained for six-hourly means (Fig. 2a, compare red lines with dark purple line; Fig. 3c). The alignment between observed Ta and RH extremes and the unsurvivable threshold for young adults suggests a causal link: in being only just above the peak Tw observed, human core temperature is consistent with the most extreme humid heat[89].

The unsurvivable threshold of older adults has also been breached. These exceedances include six-hourly means (Fig. 2a, compare red lines with darker blue line), with almost 2% of the land surface crossing these thresholds, largely in North Africa, around the Persian/Arabian Gulf, and in parts of the Indo-Gangetic Plain (Fig. 3f). This statistic contrasts starkly with the general lack of mass mortality reported in those regions (Table 1), especially as exceedances of all thresholds computed with ERA5 are probably conservative because reanalysis data underestimate the intensity of extreme heat at local scales and within living environments[61,140,160]. The lack of reported mass mortality from unsurvivable heat episodes for older adults might, therefore, reflect limitations in health surveillance data[108,109], physiological thresholds that are too pessimistic for those living in the hottest regions[120,155], or the impact of personal and community adaptations that reduce vulnerability. Similar discrepancies have been noted with uncompensable heat events for young adults[19,20,161].

Major deadly heat episodes in the mid-latitude regions have generally been associated with Ta and RH combinations below the uncompensable threshold for young and older adults (Fig. 2b,d), but the extreme heat episodes reach or exceed the threshold for older adults in the tropics and subtropics (Fig. 2c,e). However, accounting for probable cool biases of localized heat extremes could change this interpretation[61,140]. For example, in many reports, first responders to the heat victims in Paris 2003 measured Ta of 36–40 °C (at or beyond the limit of the Ta distribution in Fig. 2b) within their home environments[133]; shifting the Ta distribution by a few degrees would bring conditions close to the uncompensable threshold for older adults in Paris (Fig. 2b) and Vancouver (Fig. 2d). Similarly, it is plausible that at local scales, even young adults endured uncompensable heat in Karachi (Fig. 2c) and Lagos (Fig. 2e). Broadly, available health surveillance data are consistent with this physiological threshold perspective on mortality risk: enhanced incidences of heatstroke in older adults were noted in the Paris and Vancouver events[162,163] and 150 heatstroke patients — including young adults — were observed in one hospital alone during the Karachi 2015 event[164]. Elsewhere, the 2024 Hajj also saw >1,000 deaths in Mecca during conditions that were determined as almost certainly uncompensable for young and old adults[165].

Overall, although uncompensable heat for healthy adults (and even unsurvivable heat for older adults) has occurred at relatively large scales, the importance of crossing these physiological thresholds for human heat deaths is unclear from the historical record. Nevertheless, very steep upward inflections in mortality from future crossing events cannot be ruled out: for mid-latitude populations in which these thresholds are best characterized[18,120,155], and where detailed health-surveillance records are available[166], intensity–duration combinations of extreme heat at large scales have probably not yet reach the threshold expected to cause death by overheating for healthy adults performing minimal physical activity. Moreover, the absence of a sharp inflection in heat mortality from apparently unsurvivable heat in the hottest subtropical regions, where assumed physiological thresholds might be too conservative and health surveillance too incomplete[109], does not rule out the steep increases in heat mortality that will occur as physiological limits are breached in future, warmer climates.

Warming impacts on heat threshold exceedances

Given this potential for greatly amplified mortality, it is critical to assess how continued warming will affect uncompensable and unsurvivable heat episodes. It is generally agreed on that the risk of uncompensable heat will escalate as global temperatures climb[19,20]. At 2 °C above preindustrial levels, a scaling of the observed maximum heat index (1994–2023; Supplementary Text 2) suggests an approximate tripling of the land area (rising to ~6.7%) crossing the uncompensable threshold for young adults, generally expanding the regions already at risk[19] (Figs. 3a and 4a). An event such as Karachi 2015 would begin to experience uncompensable heat for young adults at this warming level (Fig. 4f). Uncompensable heat for older adults could be expected across ~35% of the land area at 2 °C above preindustrial levels (Fig. 4c), including during events such as Lagos 2024 (Fig. 4h). Unsurvivable heat for this warming level tends to remain generally restricted to older adults, expanding slightly the areas already at risk (Figs. 3f and 4d).

If global mean air temperature rises 4–5 °C above preindustrial levels, uncompensable heat for younger adults would affect ~40% of the land area (Supplementary Fig. 2), although the cooler mid-latitude regions (Europe) could remain mostly unaffected[19] (Fig. 4a). In the hottest regions, uncompensable heat is projected to become extremely common at this level of warming, occurring almost continuously during daytime in subtropical hotspots (for example, in Hudaydah, Yemen), and emerging in the hottest hours in tropical cities such as Lagos[19], including for an event such as that in 2024 (Fig. 4h). Older adults could also become increasingly affected by uncompensable heat for 4–5 °C of warming (Fig. 4c), impacting >60% of the land area (Supplementary Fig. 2), and an event such as Karachi 2015 would be almost continuously uncompensable for this age group (Fig. 4f). Unsurvivable heat would also begin to emerge as a threat to younger adults in the hottest subtropical regions (Supplementary Fig. 2; Fig. 4b), and events such as Karachi 2015, Paris 2003 and Vancouver 2021 could generate unsurvivable heat for older adults, especially if RH declined in these mid-latitude cities (Fig. 4e–g).

These assessments of threshold crossings are, however, subject to important caveats. First, at more localized scales, threshold crossings would be more extensive at all levels of warming[20]. Extremely rare events could also lead to threshold crossings at much lower warming levels. For example, even in the 1940–2021 climate, the maximum possible Ta in Paris (~46.6 °C), with implied RH of ~5 %, would be around the uncompensable and unsurvivable thresholds for older adults[101] (approximately where the blue lines converge in Fig. 2a). Second, all projections of uncompensable (and unsurvivable) thresholds are sensitive to assumptions about the partitioning of heat accumulation under anthropogenic warming between the sensible and latent terms (Box 1), which is less robust across climate models than the change in moist enthalpy[167]. The failure of models to capture observed declines in RH also cautions that projected increases in uncompensable heat events could be biased low, given that less moist enthalpy is required to breach these thresholds if RH falls (Supplementary Fig. 1, Supplementary Text 2). For example, a pessimistic (but not unrealistic) 5% reduction in RH[168] approximately doubles the area of uncompensable heat for young adults in a 2 °C warming scenario, relative to a scenario in which RH remains unchanged (Supplementary Figs. 2 and 4).

The urgent need to improve the understanding of energy partitioning is also well illustrated by considering the most common thermodynamic state during extreme heat events (rectangular region in Fig. 2a). These combinations correspond to Tw = 26–27 °C over the tropical oceans (Supplementary Fig. 3), sufficient to be uncompensable for young adults if reached with hot and dry pairings (for example, 47–48 °C and 20% RH) without exceeding the convective cap[76]. Land surface changes such as deforestation — which increase the near-surface sensible heat component at the expense of the latent content[169] — could, therefore, bring forward the arrival of large-scale uncompensable conditions in certain regions such as the Amazon Basin[170]. However, interventions which increase surface moisture could delay the arrival. These sobering projections underscore the urgency of adaptation.

Minimizing the mortality of heat extremes

Although precisely quantifying future heat mortality risk is fraught, physiological assessments and epidemiological projections agree qualitatively on the rapidly escalating heat mortality risk with ongoing warming. The human body does have some limited ability to develop improved physiological heat compensation through regular exposure[171–173], but adaptation will be needed. Current and necessary adaptations — referring only to adjustments in human systems to moderate harm from extreme heat[174], not any biological mechanism — are now discussed.

Existing adaptations to extreme heat

Heat vulnerability is strongly shaped by individual adaptations strategies[130]. For example, the heat balance of individuals can be modified by adjusting their attire[175] (namely, reducing insulation from clothing), deploying personalized cooling strategies[176] (for instance, fan use or dousing with cool water), moving to cooler environments[177] (such as indoor rooms which heat up slowly during extreme events)[140] or cooling their surroundings (through natural ventilation or with air conditioning)[178], or modifying physical activity levels (for example, resting)[179]. Changes in physical activity can also be reflected in working practices, including shifting energetically demanding tasks and work hours to cooler times of the day[180].

A variety of community-level policies can also help minimize mortality impacts from extreme heat. For example, heat-health warnings can be triggered if dry or humid heat measures exceed a critical level[181], determinable from epidemiological evidence[182]. Accompanying

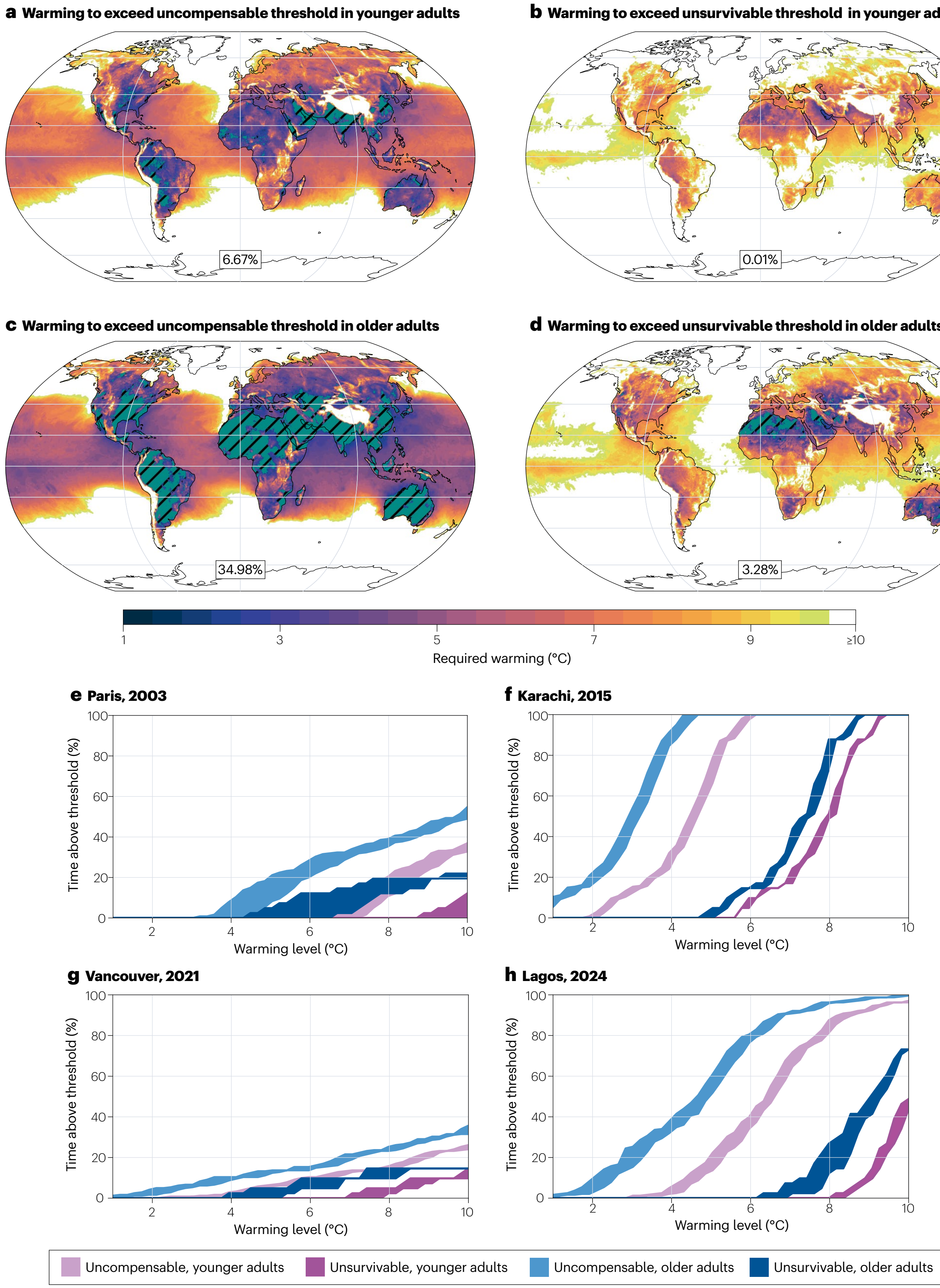

a Warming to exceed uncompensable threshold in younger adults
6.67%
b Warming to exceed unsurvivable threshold in younger adults
0.01%
c Warming to exceed uncompensable threshold in older adults
34.98%
d Warming to exceed unsurvivable threshold in older adults
3.28%
1
3
5
7
9
≥10
Required warming (°C)
e Paris, 2003
f Karachi, 2015
g Vancouver, 2021
h Lagos, 2024
Time above threshold (%)
Warming level (°C)
0
20
40
60
80
100
2
4
6
8
10
Uncompensable, younger adults
Unsurvivable, younger adults
Uncompensable, older adults
Unsurvivable, older adults

Fig. 4 | Projected exceedance of critical thermal limits. a, The amount of anthropogenic warming since preindustrial period required for the maximum 30-year heat index to exceed the uncompensable threshold for younger adults (18–40 years old)[18] from scaling Tw according to simulated CMIP6 response. The scenario assumes that humid heat rises at the projected rate in Fig. 1f and that relative humidity stays unchanged (Supplementary Text 2). Percentages indicate the land surface area (hatched) to experience at least one crossing of the threshold for 2 °C warming. White areas indicate regions in which more than 10 °C is required to breach the limits. **b**, As in panel **a** but warming required to exceed the unsurvivable threshold for a 6-h exposure[18]. **c**, As in panel **a** but for older adults (>65 years old). **d**, As in panel **b** but for the unsurvivable threshold in older adults[18]. **e**, The proportion of time that would exceed uncompensable and unsurvivable limits if conditions analogous to the 2003 Paris, France, heat event occurred at different warming levels, with relative humidity held constant (lower bound) or decreased by 5% (upper bound). **f**, As in panel **e** but if the conditions that occurred are analogous to those of the 2015 Karachi, Pakistan, heat event. **g**, As in panel **e** but if the conditions that occurred are analogous to the 2021 Vancouver, Canada, heat event. **h**, As in panel **e** but if the conditions that occurred are analogous to the 2024 Lagos, Nigeria, heat event. All city scaling is performed on a 10-day time series from the ERA5 grid point registering the maximum daily-mean heat index in the city region (Supplementary Text 2 and Supplementary Table 2). At large scales, uncompensable and unsurvivable heat would mostly be restricted to the tropics and subtropics at 2 °C warming since preindustrial period; above ~4 °C of warming, the mid-latitude regions would be increasingly at risk of uncompensable heat and the hottest regions would be at higher risk of unsurvivable heat.

public advisories tend to emphasize behavioural strategies to dissipate metabolic heat (or limit its production), reduce exposure (for example, highlighting availability and awareness of cool refugia or cooling centres — opening buildings with air conditioning to the general public[183]) and encourage surveillance of vulnerable individuals (particularly the elderly), as social isolation is a key factor driving mortality. These heat-health warning systems are becoming more commonplace, but as of 2020, they were present in only 23% of countries worldwide, with the majority concentrated in Europe and Southeast Asia[184]. The effectiveness of such systems is also unclear, with reductions in heat mortality risk reported in some cases (for example, New York City (USA)[185] and Ahmedabad (India)[186]), but mixed results elsewhere; difficulties in establishing control groups are a major challenge in evaluating their success[187]. More research is, therefore, required to evaluate the effectiveness of warning systems, especially in the context of a changing climate that will increasingly challenge historically appropriate responses[188].

Longer-term adaptation in the built environment can also help reduce exposure to extreme heat. Such interventions include optimizing the design of indoor environments to feel cooler[189]. Outdoors, Ta generally reaches higher values in cities, including during extreme events[190], in part owing to reduced evaporative cooling from drier urban surfaces[191]. Increasing the area of moist surfaces in cities, for example, with greenspace or water features, can therefore lower Ta[192]. However, the potential of such land surface modifications to combat humid heat is less clear, as discussed below in the context of adapting to levels of heat without historical precedent.

Adapting to the most extreme heat

Although existing adaptations are, in principle, suited to reduce heat-related mortality, and have already achieved some success[185,186], future heat might render them inadequate as physiological frontiers are crossed. Air conditioning, for example, is one of the most obvious solutions to heat-related mortality[151], yet its potential to reduce uncompensable heat risk is limited: it is currently too costly and energy intensive to be widespread in poorer countries and communities[193]; it adds anthropogenic heat to the urban boundary layer[194]; it elevates energy demand[195], increasing CO_2 levels; it cannot protect those who must venture outside or who cannot access indoor spaces[180,196,197]; and power system failures (from grid overload or weather-driven infrastructure damage) could leave many dangerously exposed[188,198]. Renewable energy systems designed as microgrids that are robust to catastrophic failure could minimize some of these issues[199], as could incorporating passive cooling technologies into building design[200].

Intolerable heat can also be mitigated against through land surface modifications. For example, moistening of urban surfaces, in addition to irrigation and afforestation outside of cities, moves the local climate to a cooler, more humid state[31,201], with less tendency to cross critical thresholds. However, higher surface moisture fluxes also elevate moist enthalpy in some regions[31,40,201], and the largest increases in uncompensable heat are generally anticipated in humid climates wherein the potential for evaporative cooling is limited[19]. Measures requiring freshwater must also be assessed in the context of probable reductions in its availability during extreme heat events[202]. Alternatively, reducing surface net radiation (for instance, by enhancing surface albedo) can lower near-surface heat, but such measures can also affect precipitation patterns if deployed at sufficiently large scales[203]. The potential of land surface modifications to reduce the risk of uncompensable heat therefore requires careful, regionally differentiated evaluation.

Atmospheric aerosol loading has also been proposed as a strategy to reduce extreme heat. Such loading decreases net surface solar radiation and, hence, offers a tool for regional heat reduction[204]. These modifications are contentious because any potential cooling benefits would need to be weighed carefully against other impacts, such as worsened air pollution or changes to precipitation patterns[205]. Furthermore, adopting a humid heat perspective complicates even the physical expectation for increased cooling, with results for South Asia indicating that increasing aerosol concentrations can amplify the latent heat content of the atmosphere, elevating moist enthalpy despite reducing dry heat[35]. Therefore, the extent to which local atmospheric aerosol injection could help reduce extreme humid heat remains unclear, even if the other concerns could be assuaged.

Failure of any adaptation efforts could be catastrophic for human life, leaving managed retreat — strategically relocating communities to locations less exposed to extreme heat — as a potentially viable, though controversial, option in some regions. If done properly, it could be effective and equitable[206]. Moreover, it would be preferable to the autonomous migration that might already be occurring[207] and which could occur at much larger scales in the future[208]. A related unresolved question is the varying level of heat deemed intolerable within and across communities, beyond which relocation would be the option preferred by residents. Answering such questions is extremely complex, depending primarily on socioeconomic, political and cultural factors[209], which are themselves influenced by climate change.

None of these adaptations are cost free. Limiting anthropogenic warming remains the most sound strategy for avoiding the most severe heat events[19,20].

Summary and future perspectives

Understanding of the most extreme heat events and their exacerbation with climate change has improved. Large-ensemble climate modelling has characterized heat events beyond historical norms[63,93], whereas a moist-convective framework has identified their theoretical upper limits[71,76]. Observations and model projections agree that extreme dry heat over land increases faster than global mean Ta, exceeding twice the rate in key hotspot regions (such as in Amazonia and Western and Central Europe). Physical upper bounds on extreme Ta in mid-latitude regions – which can be ~10 °C higher than observed maxima (even without further climate change) – are increasing at a similar rate, leaving high potential for record-shattering Ta[93,101] in the regions suffering the deadliest recorded heat events. Observations, model projections and convective theory generally agree on more spatially uniform changes in Tw extremes, generally increasing by less than 1 °C for each degree of warming for tropical and subtropical regions where Tw has historically been highest.

This improved understanding of changes to the most extreme heat places the evolving heat mortality risk in context and highlights key uncertainties. Statistical estimates indicate that heat mortality events expected every ~100 years in the climate of the year 2000 could generally be anticipated every few years if warming reached 2 °C above preindustrial levels. However, much higher heat mortality cannot be ruled out if key physiological limits in heat tolerance are breached. Accordingly, there is an urgent need to plan for a heat hazard that is capable of rendering existing coping strategies insufficient. A repeat of the 2015 Karachi heat wave, for example, would probably see the uncompensable threshold for young adults approached at large scales once warming reaches 2 °C above preindustrial levels – a level of warming that would enable a repeat of the Lagos 2024 event to breach the uncompensable threshold for older adults. Although mid-latitude regions, characterized by the Paris (2003) and Vancouver (2021) events, generally require more warming (4–5 °C for Paris) before experiencing substantial increases in uncompensable heat for older adults, it is physically plausible that very extreme events could breach the limits much sooner, especially at local scales. Hence, establishing cool refugia supported by resilient, renewable energy systems should be an urgent priority for the hottest regions such as South Asia and West Africa, but it should also be pursued in the mid-latitude regions to prevent very severe (and potentially surprising) impacts.

However, key questions about the most intense heat events persist. On the physical side, changes in the convective cap on maximum near-surface heat depend on fine-scale physics that are currently highly parameterized[76,96]. High-resolution convection-permitting models should be used to assess how these limits tend to change with warming, particularly for the hottest, most densely populated sub-tropical and tropical regions (for example, the Indo-Gangetic Plain and Southeast Asia). Even if connections between warming levels and upper heat limits are well-constrained, interannual variability in global temperature – driven, in part, by internal variability as in 2023 (ref. 210) – could lead to the earlier emergence of heat extremes far beyond historical precedent. Integrating such natural drivers into predictive models[51] could, therefore, help provide valuable early warning of unprecedented heat.

The dependence of human heat tolerance on sensible and latent partitioning highlights the need to understand combinations of Ta and RH that are physically plausible[71]. Storylines of change – used alongside climate model projections which struggle with heat partitioning – could use these plausible limits to inform adaptation planning. For example, scaling of ERA5 Tw during the most extreme heat index conditions (1994–2023) using the ensemble mean CMIP6 sensitivity (Fig. 1f) revealed that uncompensable heat for young adults could impact an area roughly double the size if RH declined by 5%, rather than stayed the same (Supplementary Text Section 2, Supplementary Figs. 2 and 4). The uncertainty in heat partitioning could also be reduced if anthropogenic processes (such as irrigation[86]) and natural feedbacks (for instance, between drought and wildfire[87]) were represented better in climate models.

Improved physical understanding and process representation would also benefit city-scale assessments of heat risks. For instance, physical modifications to urban environments (including tree planting) can modulate boundary layer heat budgets differently depending on the regional climate[46]. Strong understanding of these variations is, therefore, critical to avoid maladaptive attempts to cool cities. However, in general, fine-scale intra-urban variability of extreme heat and its drivers present observational and computational challenges[139,160]. These observational challenges could be overcome through the wider deployment of low-cost environmental sensors[211]. The computational challenges would probably benefit from the application of machine-learning techniques[190,212].

Improved understanding of the uncompensable thresholds is also necessary. In particular, information for populations other than healthy unacclimatized North Americans[120,155], and concerning the relationship between uncompensable and unsurvivable heat at different exposure times[18,20,157,161], would clarify the potential impacts of projected crossing events. Given their existing proximity to uncompensable thresholds, populations – especially older adults in the hottest regions (such as in North Africa and South Asia) – should be a priority for this physiological research. This understanding would help adaptation planning and inform mitigation ambitions. Indeed, the very close alignment between the most severe heat historically and the unsurvivable thresholds for young adults already underscores a very clear incentive for limiting further warming. In this context, projections and storylines would benefit from more consistent use of occurrence probabilities to identify crossing events, as very different regions might otherwise appear as at risk for the same warming levels[19,20].

On the side of human impacts, more work is needed to understand contemporary and projected risks. As a priority, better representation of the hottest and least developed regions in heat mortality databases is required, with Africa and South Asia especially in need[17,109]. However, understanding of impacts must go beyond epidemiology and physiology, drawing on the social sciences to grapple with the relevant complex socioeconomic, political and cultural factors that modulate heat mortality[134]. Specifically, chronic and short-term drivers of exposure to extreme heat, and the barriers preventing individuals adopting lifesaving cooling behaviours during extreme events, should be priorities for research. Detailed case studies using qualitative methods could help develop deeper understanding in this regard. These efforts should also draw on emerging understanding of the way that compound weather hazards can increase vulnerability to extreme heat, integrating counterfactual thinking exercises to identify particularly dangerous – but as yet unseen – combinations[213]. Interacting indirect pathways to extreme heat mortality must be included in such assessments (for instance, related to infrastructure failure, food security, economic shocks, and conflict), not least because the wider biosphere is universally characterized by upper physiological limits to heat tolerance that are increasingly at risk of being exceeded[16,88].

It is a general need for more integrated research that emerges very strongly from the literature on extreme heat[214,215]. Events beyond historical precedent (potentially exceeding the limits of human heat tolerance) threaten extreme — yet still largely unknown — impacts, related to morbidity and liveability, as well as mortality. Understanding these potential impacts requires integrating physiology, epidemiology, and the medical sciences with social science to determine how ambient heat affects mortality risk, and the capacity for human adaptation to reduce vulnerability. Likewise, close collaboration with climate science is critical for establishing the potential for these lethal levels of heat to be reached — including at local scales within communities. This understanding could be developed through interdisciplinary research projects, prioritizing the most at-risk regions (for example, North Africa and South Asia) initially targeting improved forecasting of impacts, and the deployment of commensurate measures to protect life (for instance, ensuring all those at risk can access cooling centres during uncompensable heat episodes, when behavioural responses would otherwise be inadequate). Longer term, the same understanding will be critical to underpin robust adaptation. Research, policy and practice must work synergistically to address the challenges of relentlessly increasing extreme heat on a warming planet.

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