Title
Humid heat exceeds human tolerance limits and causes mass mortality

Authors
Matthews, Tom
Ramsay, Emma E
Saeed, Fahad
et al.

Publication Date
2024

DOI
10.1038/s41558-024-02215-8

Humid heat exceeds human tolerance limits and causes mass mortality

Tom Matthews*[1], Emma Ramsay[2], Fahad Saeed[3], Steven Sherwood[4], Ollie Jay[5], Colin Raymond[6], Nerilie Abram[7], Jason Kai Wei Lee[8], Shanta Barley[9], Sarah Perkins-Kirkpatrick[10], Mariam Saleh Khan[11], Katrin Meissner[4], Callum Roberts[12], Dileep Mavalankar[13], Kenneth G C Smith[14], Attaullah[15], Anwar Sadad[15], Victoria Turner[16], Andrew Forrest[17]

1. Department of Geography and Centre for Integrated Research in Risk and Resilience, King's College London, United Kingdom (*corresponding author: tom.matthews@kcl.ac.uk)
2. Asian School of Environment, Nanyang Technological University, Singapore
3. Climate Analytics, Berlin, Germany
4. Climate Change Research Centre, University of New South Wales, Sydney
5. Heat and Health Research Centre and Thermal Ergonomics Laboratory, University of Sydney, Sydney, Australia
6. Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, Los Angeles, USA
7. ARC Centre of Excellence for the Weather of the 21st Century and Research School of Earth Sciences, Australian National University, Canberra, Australia
8. Heat Resilience and Performance Centre, Yong Loo Lin School of Medicine, National University of Singapore
9. University of Western Australia and Fortescue
10. ARC Centre of Excellence for the Weather of the 21st Century and Fenner School of Environment and Society, Australian National University, Canberra, Australia
11. Weather and Climate Services, Pakistan
12. Centre for Ecology and Conservation, Exeter University, UK
13. Indian Institute of Public Health, Gandhinagar, India
14. Walter and Eliza Hall Institute of Medical Research and the University of Melbourne, Victoria, Australia
15. Weather and Climate Services, Islamabad, Pakistan
16. Luskin Center for Innovation, University of California, Los Angeles, Los Angeles, USA
17. University of Western Australia, Minderoo Foundation, and Fortescue

The hottest boreal summer on record has driven widespread humid heat mortality across every continent of the northern hemisphere. With critical physiological limits to human heat tolerance drawing ever closer, this Comment highlights the urgent need to limit further climate warming and emphasises the adaptation challenge ahead.

Sufficiently high combinations of air temperature and humidity (levels of 'humid heat') can be lethal to humans. Most heat-related mortality occurs in older adults and those with existing disease, via cardiovascular and respiratory pathways[1]. However, thermodynamic laws mean that there are upper limits to the levels of humid heat that even the healthiest can tolerate[2]. Our highly sophisticated thermoregulatory strategies – not least sweating – simply cannot prevent overheating once air temperature and humidity exceed critical thresholds. If such 'uncompensable heat' is sufficiently long-lasting, lethal increases in internal body ('core') temperature can result[1].

The stark reality of an immutable upper limit to humid heat tolerance was highlighted in a landmark 2010 paper[2], but only recently have laboratory studies identified levels of humid heat above which core temperature cannot be held at a safe level for scenarios of minimal activity (e.g., standing and talking). These 'uncompensable thresholds' differ significantly across ages, corresponding to wet-bulb temperatures of ~25 to 31°C for younger adults[3], and ~23 to 28°C for older adults[4]. Physiological modelling studies have been able to reproduce these limits[5], allowing uncompensable thresholds to be defined across a broad range of air temperatures and relative humidities (Box Fig. 1b).

Around 4% of global weather stations have already recorded at least one six-hour period of uncompensable heat[6]. These crossing events have occurred in the tropics and subtropics, where in the most impacted regions – for example, around the Persian/Arabian Gulf, across the Indo-Gangetic Plain, and in Southeast Asia – there may already be multiple uncompensable heat events each year[6]. Ongoing human-caused climate warming and increasing humidity will intensify these potentially lethal humid heat risks[6,7], with rapid escalation anticipated even for relatively limited additional warming. Analysis from Powis et al.[6], for example, indicates that the fraction of weather observing sites in Europe experiencing at least one six-hour uncompensable episode per-century could rise almost ten-fold (from 2.9 to 24.5 %) if warming increases from 1°C to 2°C above preindustrial. In North America, once-per-decade uncompensable heat events would become almost as widespread for the same change in warming level, with the proportion of weather observing sites affected rising from 7 to 20.9 %.

Challenges in using uncompensable heat to infer mortality

Whilst the importance of uncompensable heat as a potential inflection point in health consequences is clear, key knowledge gaps currently preclude being able to quantify the lethal impacts of uncompensable heat. First, there is not *one* uncompensable threshold even within age groups, but a range depending on individual characteristics, such as levels of acclimatisation to humid heat, and the presence of co-morbidities[8,1]. Second, uncertainty in the relationship between uncompensable and *unsurvivable heat* remains understudied. By definition, conditions above the uncompensable threshold unavoidably lead to metabolic heat accumulation in the body, but how inevitably and how quickly that translates into fatal overheating is less clear[9].

Even perfect physiological understanding cannot presently be translated into accurate mortality projections due to tightly coupled unknowns in human behaviour and exposure to extreme humid heat. Behaviourally, for example, greater clothing coverage can reduce heat tolerance, whereas dousing or immersion in cool water can increase it[10]. Moreover, access to cool (e.g., air conditioned) refugia can cause *individually experienced* conditions to be compensable, even when the outdoor environment is not. On the other hand, for those without such access, the outlook is more concerning – not least because humid heat, both indoors and outside, is often more extreme in urban environments than is recorded at official weather stations[11].

These seemingly intractable challenges of generating physiology-based mortality projections have led to statistical approaches being used to link excess mortality to extreme temperatures and humidity levels. However, such measures are poorly equipped to quantify the lethal consequences of overstepping physiological limits in a future climate far beyond the reference of human history.

Widespread mortality during the hottest summer on record

From North America, across Sahelian Africa, Mediterranean Europe and the Middle East, through to Southeast Asia, significant heat-related mortality during the warmest boreal summer on record highlighted the deadly threat from rising global temperature and humidity. However, what these events can tell us about the lethal potential of uncompensable heat is less clear. First, the scale of mortality impacts is challenging to establish due to well-known limitations in health surveillance data[12]. Second – and for the reasons outlined above – considerable uncertainty in individuals' behaviour and exposure limits our ability to draw conclusions about the extent to which uncompensable heat was encountered during these lethal episodes. However, one mortality event stands out as an exception. The annual Hajj pilgrimage to Mecca saw over 1,300 reported fatalities in an event during which temperature and humidity exposure could also be determined with reasonably high confidence, and where behavioural variations were heavily constrained. It provided rare insight and an unambiguous warning of the threat from uncompensable heat (Box 1).

A warning of things to come

The mass mortality events that occurred in Mecca and across the Northern Hemisphere this year may be dwarfed under further climate warming. To illustrate, Vecellio et al.[7] find that, if global warming reaches 2°C above preindustrial, mega-city Delhi (India) – with a population of over 30 million people and climbing – is projected to experience approximately 40 hours each year when temperature and humidity combinations would reach uncompensable levels for young adults[8]. If warming reached 4°C, Delhi could expect over 550 hours of uncompensable heat, and the most frequently impacted regions on Earth (e.g., around the Red Sea) could endure over 300 days per year in which daytime conditions are continuously uncompensable.

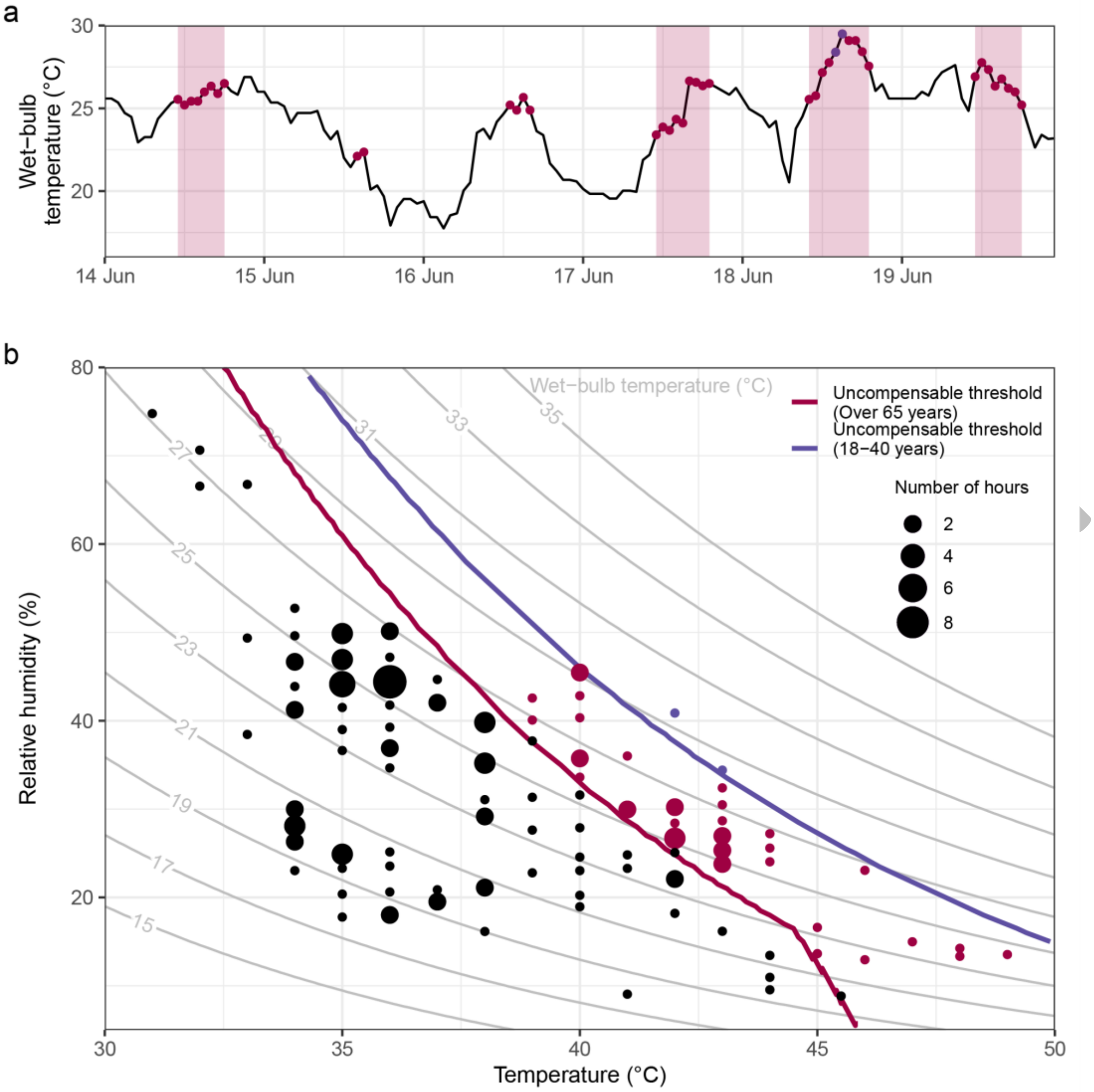
We view the mass mortality event in Mecca, during the hottest summer on record, as a stark illustration of the lethal impacts of humid heat at levels that human physiology cannot endure. We therefore urge that mitigating global warming through radical reductions in greenhouse gas emissions, especially from fossil fuel use, remains a vital pathway for blunting the deadly threat posed by rising temperature and humidity. Societal adaptation is also critical given the unavoidable escalation in heat stress within even our near-term future. In particular, efforts must urgently address how to provide protection from humid heat beyond human physiological tolerance. These measures must be accessible to all populations; continue to function effectively despite insecurities or disruptions in energy infrastructure caused by extreme weather events[13] or other challenges; and, wherever practicable, must not contribute to driving up greenhouse gas concentrations. The mitigation and adaptation challenges are high, but the penalty of inaction from humid heat threatens to be far higher.

Box 1: **Extreme humid heat meets high exposure and vulnerability in Mecca**

The 2024 Hajj pilgrimage took place between 14-19 June, with over 1,300 fatalities reported amid extreme humid heat and a lack of universal access to reliable air conditioning. Data from a nearby weather station reveals that temperature and humidity combinations crossed the uncompensable threshold for older adults during four periods of six or more continuous hours, even without accounting for sun exposure (Box Fig. 1). The uncompensable threshold for younger adults was also breached for two hours on 18 June (Box Fig. 1a).

Physiological understanding predicts that, even if in the shade, well hydrated and resting, a potentially lethal rise in core body temperature would, at times, have been expected during the 2024 Hajj for both the elderly and young. As many of the pilgrims would have been in direct sunlight, undergoing exertion and possibly dehydrated, susceptibility to heat stress was likely greatly magnified[1]. Additional factors such as comorbidities, and a lack of acclimatisation to the severity of the local conditions for visitors from abroad, would have further increased risks of mortality from the extreme combinations of temperature and humidity.[14]

This tragedy is a present-day example of the limitations of adaptation in combating the growing risk of uncompensable heat under climate warming. Analogous to the pilgrims who lacked permits to access official air conditioned shelters, many of the world's most vulnerable simply cannot afford to install or operate air conditioning[10]. Second, relying on air conditioning is precarious because widespread power outages, already common in many vulnerable regions, are more likely to occur *during extreme humid heat episodes*[10]. Third, unless energy generation transitions rapidly to renewable sources, continued widespread uptake of air conditioning will drive further increases in greenhouse gas emissions and, subsequently, heat stress in a vicious cycle.



Box Fig. 1. Temperature and humidity combinations surpassed uncompensable thresholds during the 2024 Hajj. (a) Hourly wet-bulb temperature calculated from dry-bulb temperature and relative humidity observed at the nearest weather station (Mount Arafat, located about 20 km southeast of Mecca, with a mean surface air pressure of 980 hPa) retrieved from the Iowa Environmental Mesonet archive. Coloured points indicate when the uncompensable thresholds were breached for older (red) and younger (purple) adults. Shaded regions show periods where the threshold for older adults was breached for six or more continuous hours. (b) Points indicate hourly values in (a) (14-20th June, 2024) plotted in temperature-relative humidity space, with size proportional to the number of hours experiencing that combination (see legend). Coloured points indicate when the uncompensable thresholds were breached for older (red) and younger (purple) adults. Uncompensable thresholds (colored lines) are taken from physiological models[5] for healthy adults, assuming indoor or shaded conditions and minimal activity (~1.8 metabolic equivalents).

Author contributions

T.M., E.R., F.S. S.B, S.S., A.F. and O.J. conceptualized the Comment. E.R. processed observed data and made the figure. T.M., E.R., S.S., O.J, and S.B drafted the manuscript. All authors contributed ideas and edits to the Comment.

Competing interests

The authors declare the following competing interests:

- All authors are members of the Lethal Humidity Global Council, an assembly of dedicated leaders and global experts to protect humanity against lethal temperature and humidity combinations, and the risks posed by climate change more generally.

Acknowledgments:

The authors are members of the Lethal Humidity Global Council. Whilst the views stated here are the authors' own, our initiative is additionally supported by the following members of the Council:

Sagnik Dey, Indian Institute of Technology Delhi, India
Emily Shuckburgh Director of Cambridge Zero, Cambridge University, UK
Vidya Venugopal, Sri Ramachandra Institute of Higher Education and Research, India
Tim Lenton, Exeter University
Louise Slater, Oxford University
Bill Hare, Adjunct Professor Murdoch University & Climate Analytics
Robert Glasser, Senior Fellow Australian Strategic Policy Institute (ASPI)
Douglas McCauley, University of California Santa Barbara
Ambarish Dutta, Professor of Epidemiology at Public Health Foundation of India (PHFI)
Associate Professor Kamiar Mohaddes, Cambridge Judge Business School

References

1. Ebi, K. L. *et al. The Lancet* **398**, 698–708 (2021).
2. Sherwood, S. C. & Huber, M. *Proc. Natl. Acad. Sci.* **107**, 9552–9555 (2010).
3. Wolf, S. T., Cottle, R. M., Vecellio, D. J. & Kenney, W. L. *J. Appl. Physiol.* **132**, 327–333 (2022).
4. Wolf, T. S., Cottle, R. M., Fisher, K. G., Vecellio, D. J. & Larry Kenney, W. *Commun. Earth Environ.* **4**, 1–10 (2023).
5. Vanos, J. *et al. Nat. Commun.* **14**, 7653 (2023).
6. Powis, C. M. *et al. Sci. Adv.* **9**, eadg9297 (2023).
7. Vecellio, D. J., Kong, Q., Kenney, W. L. & Huber, M. *Proc. Natl. Acad. Sci.* **120**, e2305427120 (2023).
8. Kenney, W. L. & Zeman, M. J. *J. Appl. Physiol.* **92**, 2256–2263 (2002).
9. Lu, Y.-C. & Romps, D. M. *Environ. Res. Lett.* **18**, 094021 (2023).
10. Jay, O. *et al. The Lancet* **398**, 709–724 (2021).
11. Ramsay, E. E., Hamel, P., Chown, S. L. & Duffy, G. A. *One Earth* **7**, 2–5 (2024).
12. Harrington, L. J. & Otto, F. E. L. *Nat. Clim. Change* **10**, 796–798 (2020).
13. Matthews, T., Wilby, R. L. & Murphy, C. *Nat. Clim. Change* **9**, 602–606 (2019).
14. Abdelmoety, D. A. *et al. BioMed Res. Int.* **2018**, 5629474 (2018).