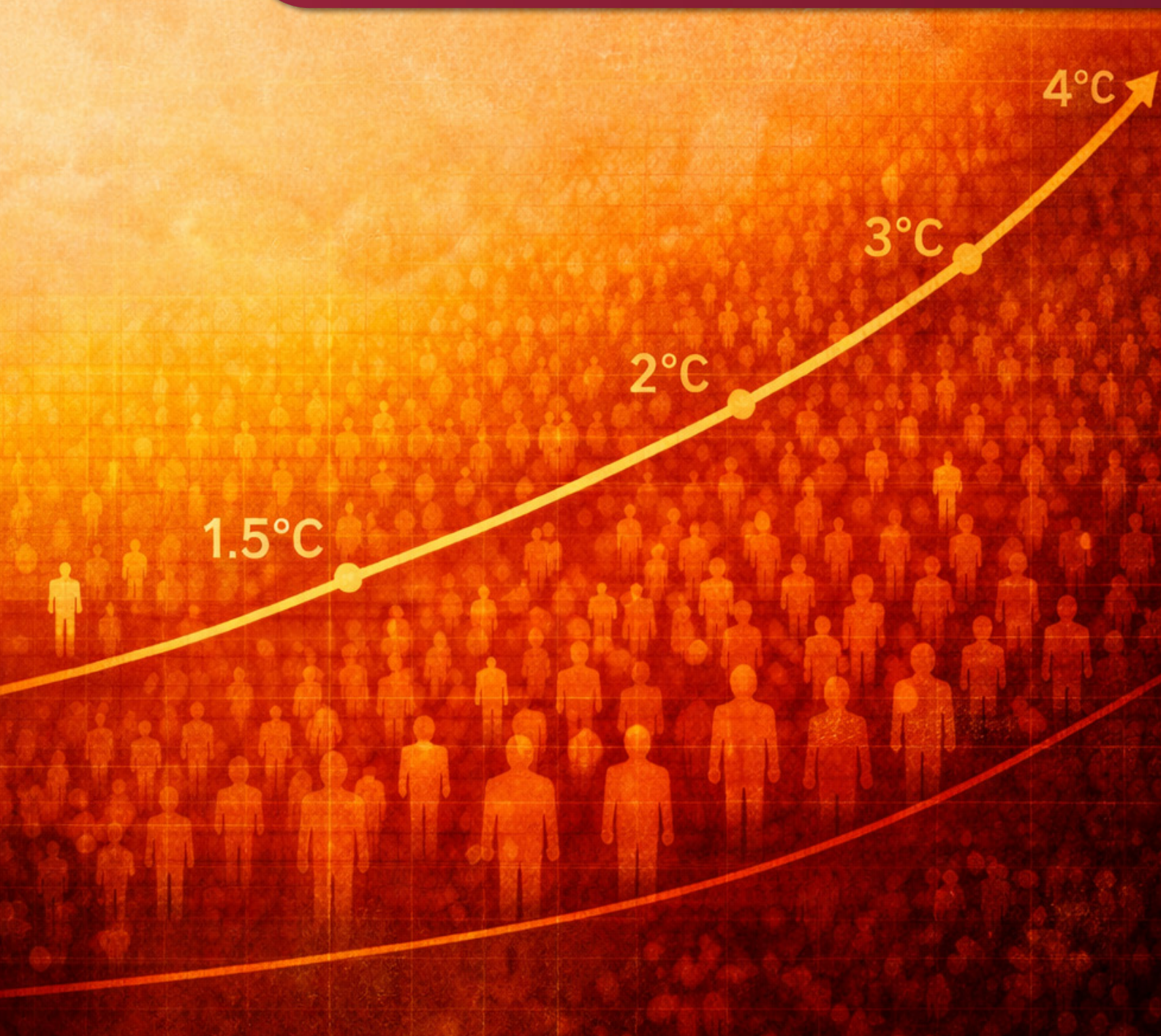


Lethal humidity and the systemic risks of climate change

REPORT

Dr Robert Glasser



About the author

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AI contributed no ideas to this report.

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Dr Robert Glasser



25
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Executive summary

One of the great challenges in understanding the extraordinary consequences of global warming is our tendency to think in silos. Climate change is still often regarded as solely an environmental issue—and is generally coordinated in governments by environment ministries—rather than as a systemic crisis that affects every aspect of society. That same tendency helps to explain why the rising threat of lethal humidity, which is a combination of extreme heat and high humidity that can exceed the limits of human survival, has been overlooked until relatively recently.

Climate change is not only warming the planet but also increasing humidity, because warmer air holds more moisture. The role of climate change in amplifying extreme heat and heatwaves has been widely studied, but only recently have the implications of its combination with high humidity been well understood. High humidity significantly lowers the temperature at which severe human health impacts occur. The synergistic and accelerating effect of high temperature and high humidity is rapidly moving large, densely populated regions of the planet towards the limits of physiological survivability.

This report uses ‘lethal humidity’ as a focal concept but focuses primarily on the broad category of extreme humid-heat events that are increasingly approaching, and in some regions exceeding, that threshold. It focuses on the rising threat posed by extreme humid heat, both as a stand-alone climate hazard and as part of a more complex pattern of interconnected hazards intensified by climate change. It highlights the accelerating impacts of extreme humid-heat occurrences and how they’ll both amplify and be amplified by other climate-related events happening simultaneously or consecutively.

The report’s main objective is to show that those impacts aren’t isolated: they cascade through societies, magnified by other climate hazards, such as storms and flooding.

The first section examines how humid-heat hazards have evolved in frequency and intensity and surveys the societal impacts of three historical humid heatwaves: Chicago (1995), South Asia (2015), and Brazil (2023). It identifies common themes across the three cases, focusing particularly on key cascading societal consequences.

The second section explains how rapidly climate change is causing humid-heat extremes to reach and surpass lethal humidity thresholds. It identifies six defining features of climate change that shape what societies can expect from extreme events such as humid heatwaves. It also summarises climate modelling projections of humid-heat extremes and how they may be compounded by other climate hazards emerging simultaneously.

The third section focuses on Indonesia, one of the most geopolitically important and rapidly developing countries in the Indo-Pacific, where extreme humid heat will rapidly become a defining climate risk. Over the past decade, Indonesia has risen into the top five nations globally for exposure to heatwave days. The section also illustrates how humid-heat extremes may reach lethal humidity levels in future and interact with other climate hazards, such as flooding, drought, sea-level rise and energy-system stress, creating major cascading societal disruptions in the country.

The final section summarises the main findings and identifies key policy and research priorities to address the growing likelihood that humid-heat extremes will surpass lethal humidity thresholds, with severe consequences for humanity. It notes that each new decade will expose many tens of millions of additional people to deadly humid-heat extremes. As much as 50%–75% of the *global* population will be exposed by late this century.

That dire trajectory elevates lethal humidity from a high-impact risk to a *systemic* global threat, requiring rapid reductions in greenhouse gas emissions and decisive policy responses. The Lethal Humidity Global Council¹ identifies four urgent and necessary shifts:

1. Achieving real zero emissions through complete fossil-fuel phase-out and renewable replacement.
2. Removing barriers to green industry, including fossil-fuel subsidies, before 2030.
3. Matching incentives and disincentives to risk through carbon pricing.
4. Using economic stimulants to drive green growth and transformation.

While those shifts are essential to limit future risk, they can’t fully avert the impacts already set in motion. Accordingly, this report recommends the following additional measures to improve understanding of lethal humidity and to prepare societies for accelerating impacts, many of which are now unavoidable following decades of inadequate climate action.

Recommendations

1. Accelerate research on humid-heat impacts and human survivability.

Laboratory, field and epidemiological studies should be expanded to improve understanding of physiological limits, including how livability² will be diminished as the survivability threshold is approached. Research must also examine socio-economic and environmental impacts that remain understudied.

2. Expand and focus research in less developed countries.

Humid-heat research should prioritise countries in the tropics, which are disproportionately exposed and vulnerable, and should strengthen domestic scientific capacity to support national planning and responses.

3. Investigate the economic and labour-productivity impacts of warming.

Humid heat is already responsible for labour losses comparable to those caused by the Covid-19 pandemic. This evidence should be used for far greater advocacy and policy impact.

4. Identify and mitigate cascading societal impacts.

Humid heatwaves can drive electricity demand spikes that trigger blackouts, interrupt water systems, and disrupt transport—effects that quickly multiply exposure. Research should clarify where and under what circumstances those cascades occur and how they can be interrupted or reduced.

5. Address the interactions between humid heat and other climate hazards.

Humid and dry heatwaves increasingly coincide, with serious implications for sectors such as agriculture. Co-occurrence with extreme rainfall, storm surges and coastal flooding is also rising, especially in low-latitude coastal regions. Those and many other intersecting hazards linked to climate change require urgent investigation to inform measures to mitigate the impacts.

6. Prioritise adaptation planning for tropical coastal cities.

By 2100, around 3 billion people may live in tropical coastal cities exposed to high humid-heat stress alongside sea-level rise, storm surges, flooding, urban heat islands and deep social vulnerability. Cities such as Chennai, Manila and Dhaka should be focal points for research, adaptation investment and risk reduction.

7. Assess the extraordinary risks facing China.

China's rapidly growing exposure to extreme heat-humidity events—potentially affecting up to 80% of its population under high emissions—should be a priority for policy and security analysts within and outside the country.

8. Recognise that reduced recovery time will amplify impacts.

Climate change is increasing the frequency and sequencing of humid heat, floods, droughts and coastal inundation. With less time to recover between events, community resilience will erode rapidly. Emergency-management and adaptation planners must incorporate this more realistic understanding rather than relying on outdated assumptions of rare or seasonal disasters.

9. Strengthen and reform heat action plans.

Heat action plans (HAPs) should:

- integrate human physiology³ in the models used for these warning systems
- incorporate humidity into all aspects of early warning, communication, planning and response
- address social inequalities and the needs of disadvantaged groups
- integrate climate projections and define longer term investments, such as urban infrastructure improvements.

A comprehensive 'toolbox' of measures—from essential-services strengthening and social-protection initiatives to urban design changes, workplace adaptations, cooling infrastructure and community-level programs—should be shared widely with governments, development banks and aid agencies.

10. Treat keeping people cool in a warming climate as a global grand challenge.

More than 1.1 billion people already lack adequate cooling, and nearly 2 billion residents of countries with hot climates may lack access to air conditioning (AC) in 25 years. Ensuring resilient electricity grids is essential, but alternatives to centralised power are needed. Expanding off-grid solar-photovoltaic (PV)-based cooling, including AC-capable systems, offers a promising and increasingly affordable option. Similarly, implementing numerous other interventions at the landscape, building (such as reflective roofing) and individual levels should be elements of the grand challenge.

11. Invest now in planning and preparedness.

Evidence from Shanghai, Chicago and Karachi shows that investments in planning, preparedness and public awareness can significantly reduce mortality in extreme events. Those successes should be shared widely and expanded globally.

The stakes are enormous, and the window of opportunity to mitigate the climate impacts is closing. Governments, the private sector and civil society must act rapidly, decisively and purposefully to ensure that lethal humidity remains a rare occurrence, rather than a deadly reality for billions of people.

1. Humid heatwaves: escalating extremes and historical impacts

Humid-heat extremes are among the most dangerous and least understood consequences of climate change. This section introduces the concept of lethal humidity and traces how humid-heat extremes have evolved in frequency and intensity. It draws on three historical cases—Chicago (1995), South Asia (2015) and Brazil (2023)—to illustrate some of humid heat’s key cascading societal impacts.

Heat stress and lethal humidity

Heat stress is influenced by a wide range of environmental, occupational and personal factors. A particularly important environmental factor is humidity, which can lower the temperature at which severe human impacts emerge. Both dry and humid-heat extremes occur globally, but their timing and locations differ, and their effects vary across sectors such as health, agriculture, water and ecosystems.⁴ Many definitions of heatwaves now incorporate ‘humidity’ in recognition of the critical role it plays in amplifying heat’s effects on the human body.

Under conditions of high temperature and humidity, the body’s main cooling mechanism—perspiration and evaporative heat loss—becomes insufficient because the air is already saturated with moisture. Prolonged exposure causes a dangerous rise in core body temperature. To compensate, the body redirects blood from internal organs to the skin to offload heat. A core problem is reduced oxygen supply to the gut. That lack of oxygen damages the gut lining, making it more permeable and allowing bacteria to pass into the bloodstream. The body responds with an intense, system-wide inflammatory reaction, which can trigger widespread coagulation and death. Those impacts can build on each other, with the failure of one organ worsening others, leading to multiple organ failure and death. One study identified 27 distinct pathways through which those cascades can trigger organ failure.⁵

Additionally, because the body diverts large amounts of blood to the skin to help with cooling, the heart must work harder to maintain blood pressure. That increased cardiac workload, which is reflected in a much higher heart rate, raises the risk of a catastrophic cardiovascular event in people with underlying heart conditions, such as coronary artery disease.⁶

Heat combined with humidity is measured as the ‘wet-bulb temperature’ (Tw), which is the lowest temperature that air can reach through evaporative cooling. It provides a measure of how easily perspiration can evaporate and therefore how effectively the human body can cool itself. At 40°C and 50% relative humidity, Tw is 31°C; at 40°C and 75% humidity, it’s about 36°C. At 100% humidity, the wet-bulb temperature equals the air temperature because no evaporation is possible.⁷

Early research suggested that exposure to Tw of 35°C for six hours marks the limit of human adaptability, as dissipating extreme heat becomes impossible.⁸ The 35°C mark has since been widely used as the *lethal humidity* threshold. This report’s discussion of ‘extreme humid heat’ refers to conditions that have relatively infrequently surpassed that threshold but will increasingly do so as the climate continues to warm.

Vulnerability to extreme heat is highest among elderly people with cardiopulmonary and other chronic disease.⁹ Very young children and people over 65 account for most emergency-room visits and deaths during heatwaves.¹⁰ Ageing reduces blood flow to the skin and sweat gland output in response to heat stress, and older adults are more likely to have co-morbidities, such as cardiovascular disease. The upper limit of humid-heat tolerance in older adults is significantly lower—approximately 23°C to 28°C—than in younger individuals.¹¹

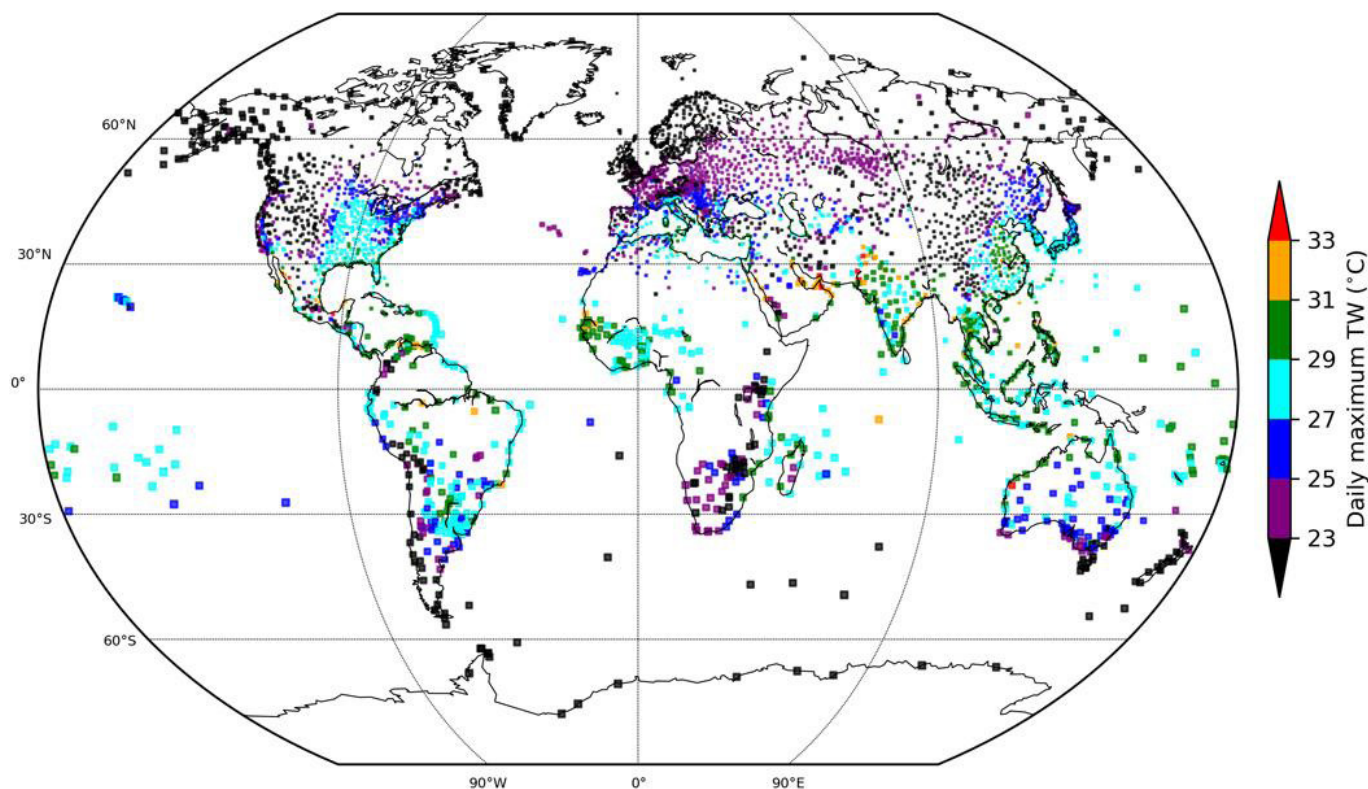
Important recent research on temperature extremes in Mexico,¹² drawing on uniquely detailed data, including station-level wet-bulb temperature estimates, found that people under 35 years old suffered most humid-heat-related deaths. It suggests that the disproportionate impact reflects behaviour and occupational factors. Young adults are more likely to work outdoors with minimal flexibility for precautionary action. The analysis suggests that, in a warming climate, the mortality burden will grow to include young people as well as the elderly. The societal impact of that shift would be profound, given the economic productivity of younger adults.

Two other measures of humid-heat stress are also used widely: the Heat Index (HI)¹³ and the wet-bulb global temperature (WBGT).¹⁴ HI is often used for communicating to the public what the temperature feels like when relative humidity is combined with air temperature. Because the index’s values were devised for shady, light wind conditions, it’s an effective measure for only a narrow range of real-world situations. In contrast, WBGT is a more complex metric of heat stress

designed for physically active populations outdoors in direct sunlight.¹⁵ It incorporates factors such as air temperature, humidity, wind speed and solar radiation.¹⁶

Until recently, it had been assumed that Tw over 33°C had rarely occurred and that lethal humidity levels (Tw exceeding 35°C—the heat stress tolerance limit) had never been observed. However, a 2020 reassessment¹⁷ of the historical data determined that many places have already exceeded Tw 33°C and that the Tw 35°C lethal humidity limit has been breached on multiple days in several locations, including in the subtropics. It also found that the overall frequency of those extreme events has more than doubled since 1979 (Figure 1).¹⁸

Figure 1: Observed global extreme humid heat



Notes: Colour symbols represent the 99.9th percentile of observed daily maximum Tw for 1979–2017 for HadISD stations with at least 50% data availability over that period. Marker size is inversely proportional to station density.

Source: Colin Raymond et al., 'The emergence of heat and humidity too severe for human tolerance', *Science Advances*, 2020, 6(19), [online](#).

Humid-heat extremes have also increased more rapidly than dry heat extremes over populated regions, relative to global land areas more generally. This means that population exposure to humid heat is increasing at a *faster rate* than exposure to dry heat.¹⁹

On average, Southeast Asia and the Indo-Gangetic Basin now experience three or more months per year of Tw exceeding 27°C.²⁰ Regions facing the largest increases include the Mekong Delta, Bangladesh / West Bengal, the Maritime Continent (the region between the Indian and Pacific oceans encompassing the archipelagos of Indonesia, Borneo, New Guinea, the Philippine islands, the Malay Peninsula and the surrounding seas), parts of the Amazon and northern Colombia.

The rapidly accelerating frequency and severity of these hazards challenge the capacity of populations to manage them effectively.²¹ As one analysis recently noted:

Communities are often only prepared for extreme temperature events within the bounds of past experience, and populations only acclimatized to the present climate. As discussed elsewhere, the likelihood of experiencing abrupt transient temperature extremes well outside of the boundaries of historical experience is increasing everywhere. Should a noncompensable heat extreme [that is, 'the set of environmental conditions under which a healthy human being can no longer maintain a stable core temperature without the assistance of external cooling'] occur in a region where the local population is unprepared and not sufficiently acclimatized, the number of excess deaths that result could markedly exceed the impacts of past local extremes.²²

The societal costs are already enormous. Two of the deadliest heatwaves on record—the 2003 European heatwave and the 2010 Russian heatwave—caused more than 70,000 and 55,000 deaths, respectively.²³ In the European heatwave, France alone lost US\$3.1 billion in agricultural output, while Russia’s 2010 economic losses exceeded US\$15 billion.²⁴

To grasp the scale of this accelerating threat, it’s useful to examine past events that illustrate the societal impact of extreme humid heat. The following surveys—Chicago (1995), India and Pakistan (2015) and Brazil (2023)—highlight how combinations of high temperature and humidity have already produced lethal outcomes across diverse regions and socio-economic contexts.

Chicago, 1995

The severe humid heatwave that struck Chicago in mid-July 1995 was the deadliest weather event in the city’s history.²⁵ It was caused by a large high-pressure system that stalled over much of the US midwest. Southerly winds pumped moist air into the region from the Gulf of Mexico, producing high relative humidity. Daily highs exceeded 38°C and evening lows stayed above 27°C but, at the peak, the HI reached 51°C—within the ‘extreme danger’ level.

An urban ‘heat island’ effect probably exacerbated the event.²⁶ Maximum daytime temperatures were 1.6°C higher in the city centre (and 2.0°C to 2.5°C higher at night) than in surrounding suburbs. Although Chicago has experienced later heatwaves with higher temperatures (for example, in 2012), none combined such sustained heat and humidity.

Seven hundred and thirty-three people died between 14 and 20 July, with mortality peaking two days after the temperature maximum.²⁷ Persistently high night-time heat and humidity offered little relief. Most victims were elderly (more than 70% were aged 65 or above) or socio-economically disadvantaged residents of poorly ventilated apartments lacking air conditioning. Some were too afraid of burglary to open their windows.

Key risk factors included being confined to bed, living alone or residing on upper floors.²⁸ Mortality risk was highest among those with less than a high-school education and lowest among those with air conditioning, transport access or social contacts (one reason women fared better than men).²⁹ Black residents faced substantially higher risk due to overlapping social isolation and economic disadvantage.³⁰

Chicago’s medical infrastructure was overwhelmed.³¹ As a leading scholar wrote:

Hundreds of victims never made it to a hospital. The most overcrowded place in the city was the Cook County Medical Examiner’s Office, where police transported hundreds of bodies for autopsies. The morgue typically receives about 17 bodies a day and has a total of 222 bays. By Saturday—just three days into the heat wave—its capacity was exceeded by hundreds, and the county had to bring in a fleet of refrigerated trucks to store the bodies. Police officers had to wait as long as three hours for a worker to receive the body. It was gruesome and incredible for this to be happening in the middle of a modern American city.³²

Power demand for cooling reached record levels on 14 June, overloading the grid. The resulting massive outages affected 40,000 people at their moment of greatest need.³³ By 15 July, 8,500 people were still without power, while utility companies implemented rolling blackouts in rural areas to maintain power to southside Chicago communities.

The power outages had additional cascading impacts.³⁴ Elevators stopped working, stranding disabled residents. Water pumps failed, cutting supply and sanitation (particularly to the upper floors of apartment buildings).

More than 3,000 water hydrants opened by residents reduced water pressure, forcing 23 emergency cooling centres to close.³⁵ Emergency crews sent to close off the fire hydrants were met by angry residents who threw bricks and rocks to prevent them from doing so.³⁶

Livestock was also affected;³⁷ 1.25 million chickens and thousands of cattle died, while milk production in neighbouring Wisconsin fell by 25%.³⁸ Infrastructure buckled: roads warped, train rails bent and bridges required constant watering to prevent locking.³⁹ The power outages also affected cold storage of food, both in homes and at markets. Local food supply chains were severely disrupted.⁴⁰ The disruptions reduced the availability of food and led to higher prices being charged by the remaining stores that were able to continue functioning. Not surprisingly, that affected low-income residents disproportionately.

Chicago’s experience in this disaster resulted in major reforms, including new heat warning systems, cooling centres and community outreach.⁴¹ That better prepared it for the second most severe heatwave of the decade, which struck just four years later.⁴² This suggests that, while consecutive disasters can undermine resilience, well-targeted adaptation can enhance it.⁴³

India and Pakistan, 2015

Although occurring only weeks apart, the 2015 Indian and Pakistani heatwaves stemmed from distinct weather systems.⁴⁴ The India event, from late May to early June, was caused by unusually strong winds blowing from the northwest, which pushed the typically stronger moist winds away from land, forestalling the arrival of pre-monsoon showers and enabling hot, dry air from desert regions in the northwest to move across much of the country.⁴⁵ In contrast, the Pakistan heatwave, from late June to early July, was driven by onshore winds, which added unusually humid conditions to the exceptional heat.

The Indian heatwave

The Indian event was predominantly a *dry* heatwave, but parts of the country also experienced record-setting *humid* heat. Indeed, those locations, generally in coastal areas, also accounted disproportionately for the deaths. By 4 June, at least 2,300 people had died nationwide, two-thirds (1,719 deaths) of whom were in Andhra Pradesh (AP), alone.⁴⁶ The daily HI at all AP monitoring stations exceeded 41°C for many days and may have exceeded 54°C on several occasions.⁴⁷

The duration of the heatwave in AP may also have contributed to its lethality. In India the average duration of extreme heatwaves is two to four days; in central and northwest India it's over six days, and in AP it's over eight days; but in 2015, the extreme humid heat persisted for 11 days in coastal areas of AP—longer than elsewhere in the country.⁴⁸

As with the Chicago disaster, hospitals and emergency services were rapidly overwhelmed across the country.⁴⁹ In Delhi, long lines of heat-distressed people formed outside of public hospitals, and wards overflowed with heat-stroke victims. As one medical officer in AP noted, 'I have worked as a medical officer in this district for 40 years and I have never seen anything like this, with so many people arriving already dead.'

It isn't surprising that power outages caused by spikes in electricity demand for cooling exacerbated the health impacts.⁵⁰ In 2015, India's electricity grid was characterised by frequent load shedding, inadequate investment, insufficient maintenance and slow responses to weather-related outages.⁵¹ The situation was especially problematic for rural populations. A survey at the time of rural households in six of the most populous northern states found outages on average occurred for 11 hours each day.

Agriculture was also affected during the heatwave. In the states of AP and Telangana, for example, close to 7 million chickens died, or 10% of the total stock.⁵² Crops in the central part of the country were affected by the drought, exacerbated by the heatwave.⁵³ Crop losses and farmer suicides were linked to the rainfall shortages and rising temperatures.⁵⁴ The state of Maharashtra suffered significant crop losses during the heatwave and recorded the nation's highest number of suicides.

The Pakistan heatwave

During the first half of June 2015, an extended period of extreme heat developed over southern Punjab, Sindh and parts of Balochistan. A persistent high-pressure ridge developed over Balochistan and adjacent areas, disrupting the usual sea breeze and trapping heat and moisture near the ground, particularly in coastal Sindh.

The resulting humid heatwave persisted for five consecutive days (19–23 June). Maximum temperatures exceeded 45°C across many parts of the region. On 20 June, Karachi experienced its highest temperature (44.8°C) in over a decade, but it was the combination of high temperature and high humidity—including at night—that dramatically elevated the risk.⁵⁵ Reports suggest that the HI peaked that same day at 66°C, which was among the highest levels ever recorded in the country and associated with extreme risk to human survivability.⁵⁶ Two days later it again exceeded the extreme danger threshold at 58.3°C.⁵⁷

More than 80,000 people in Karachi alone required treatment at hospitals, and an estimated 1,200 died, most in the period between 20 and 25 June.⁵⁸ One survivor later recalled, 'It was difficult to breathe as if the air had no oxygen.'⁵⁹ The Prime Minister described the heatwave event as 'the worst in Pakistan's history'.⁶⁰

Research suggests that Karachi residents overall were about 17 times more likely to die from a heat-related cause during June 2015 than they were in the previous June.⁶¹ Interestingly, that research also noted that age was *not* a significant risk factor, although that could possibly be because the study's data was drawn from hospital death certificates, while many elderly people are likely to have died at home or in remote health posts.

The heatwave coincided with the holy month of Ramadan, during which Muslims, who made up over 95% of Karachi's population, were expected to neither eat nor drink from dawn to dusk. Although religious leaders instructed the public to

avoid fasting during the heatwave, some observers noted that the elderly, who tended to be particularly devout, were more likely to ignore the instructions and were therefore at greater risk.⁶²

Excess deaths were reported across all demographic groups, but increased risk was associated with people with lower income and with less than a fifth-grade education. Not surprisingly, many of those victims were poor, homeless or living in unventilated and badly constructed low-cost housing, with limited access to electricity for cooling.⁶³ As one poor labourer commented:

Yesterday I just fainted and was taken to hospital, because there is no respite from the heat, and the home I go to consists of just a few bricks with planks of timber and a tin roof placed over them . . . It is like an oven.⁶⁴

As has occurred in other severe heatwaves, mortuaries were full⁶⁵ and medical facilities were rapidly overwhelmed by the event:

In hospitals, a state of emergency was proclaimed, and medical personnel were fighting to treat patients. Every hospital's heatstroke ward was either overcrowded or lacked the resources necessary to care for these patients, thus doctors were forced to admit patients to regular wards without facilities specifically designed to manage heatstroke.⁶⁶

As with the Indian heatwave, the spike in demand for electricity triggered prolonged power outages, and load-shedding cut electricity to air conditioners, fans and water pumps.⁶⁷ Water shortages were reported, particularly in low-income areas of the city and for residents of high-rise buildings.⁶⁸ It seems likely that those disruptions contributed significantly to the health impacts of the disaster, although there's inadequate data to determine the magnitude of the impacts.⁶⁹

Lack of systematic and standardised data also makes it difficult to ascertain the impact of the heatwave on the agriculture sector,⁷⁰ although some commentators indicated there had been significant damage to wheat and cotton crops.⁷¹

Brazil, 2023

Heatwaves in Brazil have increased sharply in frequency, duration and intensity, contributing to an estimated 50,000 excess deaths between 2000 and 2018.⁷² The toll is now rising rapidly.

The record-setting humid heatwave that peaked on 18 November 2023 was among the country's most severe. The rising temperatures were connected to upper-atmosphere high-pressure systems centred over the South Atlantic, which caused sinking air to clear the skies, allowing for the build-up of surface heat.⁷³ A strong El Niño probably contributed to the event. The sinking air also reduced rainfall and increased evaporation, which dried out the soil, adding more moisture to the air. Moisture coming from the Amazon and from contiguous ocean waters—which were unusually hot—contributed further to the rising humidity.

On 18 November, 11 meteorological stations in Rio de Janeiro recorded maximum temperatures of 40°C or higher, with the highest reaching 43.5°C—a record for the city. Those extreme temperatures occurred at the end of an unusually long eight-day heatwave. The accompanying high levels of humidity resulted in a peak HI level of 55.1°C—well within the 'extreme danger' HI threshold—which persisted for almost seven consecutive hours, putting large numbers of people at high risk.⁷⁴ Tens of thousands flocked to Copacabana and Ipanema beaches to escape the intense heat.

Hundreds of excess deaths were recorded during the spike in temperature.⁷⁵ The actual numbers were probably much higher due to under-reporting. The duration of the extreme event may have contributed to its lethality.⁷⁶ A subsequent moist heatwave of a significantly shorter duration struck the city four months later with an even higher HI of 62.3°C, but with no comparable impact on mortality.⁷⁷

There's limited data on the groups most affected by the heatwave, but, historically in Brazil, older adults have been particularly vulnerable due to physiological factors, such as age-related declines in heat regulation and a higher prevalence of chronic diseases, reduced mobility and social isolation.⁷⁸ Women, especially elderly women, were at higher risk due to social and economic disadvantages, including lower income and education levels and poorer overall health.

Socio-economic and racial disparities have also significantly affected heatwave-related mortality in the country. In Brazil, older adults with lower education levels and those identifying as black or brown have experienced much higher excess mortality during heatwaves than their white and more educated counterparts. The risks have been associated with structural inequalities—such as inadequate access to health care, poorer housing conditions and less access to resources like air conditioning—that limit resilience during extreme heat events.

The risk factor associated with poor housing quality is particularly acute in Brazil, where about 16 million people (8% of the population) live in densely populated, impoverished neighbourhoods, the largest of which is located in Rio de Janeiro.⁷⁹ These ‘favelas’ often become ‘heat islands’, where temperatures can be up to 8°C higher than in neighbouring communities.⁸⁰

Electricity demand surged during the heatwave, reaching a record 90,596 megawatts on 17 November 2023, triggering concerns about possible blackouts.⁸¹ Had the heatwave occurred just three weeks earlier, the death toll in Sao Paulo, the nation’s capital, might have been significantly higher. A major storm destroyed powerlines in the state,⁸² leaving 4 million customers without electricity to power air conditioners and fans and to pump water to elevated locations, including in apartment buildings;⁸³ Sao Paulo has the second-largest number of tall buildings in South America.⁸⁴ Many were still without power one week later.

The November heatwave was the eighth to hit the country that year.⁸⁵ Not surprisingly, the combination of extreme heat and dry conditions in many parts of the country had a significant impact on Brazilian agriculture.⁸⁶ Soybean planting was delayed, lagging historical averages by about 10%, and reports suggested similar concerns about delays to the second corn crop.

Brazil experienced a record dengue fever outbreak early in 2024. By August of that year the number of cases had reached more than 6.5 million, with 5,000 deaths. Evidence suggests that thermal anomalies have increased dengue fever outbreaks in Brazil⁸⁷ and that both temperature and humidity are central to transmission.⁸⁸ There’s also evidence that heatwaves can increase the risk of dengue infection⁸⁹ and delay the effects and increase the magnitude of dengue outbreaks.⁹⁰ Indeed, in February 2024, the Health Secretary of the state of Minas Gerais attributed the rapidly accelerating numbers of infections to the record temperatures experienced towards the end of 2023.⁹¹

The fact that the number of cases in 2024 spiked just at the outset of the 15–18 March heatwave highlights the potential for simultaneous compounding hazards. Reports suggested that the dengue infections had a major impact on health facilities:

In cities across the country, hospitals and doctors were stretched to the limit. There were reports of hospital beds running out and of patients being turned away in some regions.⁹²

There’s also some overlap in the populations at high risk from both heatwaves and dengue infections, in particular low-income status, low levels of education, and residing in densely populated slums.⁹³ Those factors additionally played a role in increasing the number of mosquitoes carrying the virus:

Millions of Brazilians live in densely populated, irregular communities—either called favelas or ‘the periphery’—often beyond the reach of government services and basic utilities. With unreliable plumbing, people often resort to storing water outside, creating countless mosquito breeding sites.⁹⁴

Some common themes across these humid heatwaves

This brief survey of three significant humid heatwaves illustrates several important points. The first is the challenge of collecting good data and the risk of drawing categorical conclusions from the data on the links between heatwaves and specific societal impacts, including fatalities. Heat-related deaths are often under-reported, particularly in less developed countries, for many reasons, including limited resources, lack of standardised reporting systems, and the tendency to attribute deaths to other causes, even when heat exposure is a major factor. There’s also a socio-economic dimension to under-reporting:

Heatwaves are the deadliest type of extreme weather, but they don’t leave a trail of destruction or striking images of devastation. They kill poor, lonely people in rich countries, and poor people working outdoors in developing countries ... there will be thousands and thousands of stories of poor people dying in heat that will never be told.⁹⁵

Government officials may additionally be reluctant to acknowledge heat-related deaths for political reasons. Admitting that dozens of deaths were caused by an ‘avoidable’ environmental hazard like extreme heat can result in accusations of negligence and mismanagement, risking political embarrassment or, worse, personal liability.⁹⁶

Those factors may help to explain the small number of deaths reported (2,300) from the 2015 Indian heatwave, which was among the strongest in the country’s history, at a time when about 25% of the country’s population of 1.3 billion people lived in poverty.⁹⁷

Not surprisingly, two common themes in these extreme events are the impact on health systems: rapid increases in heat-stressed populations overwhelm emergency services and hospitals; and spikes in electricity demand for cooling trigger large-scale power outages.

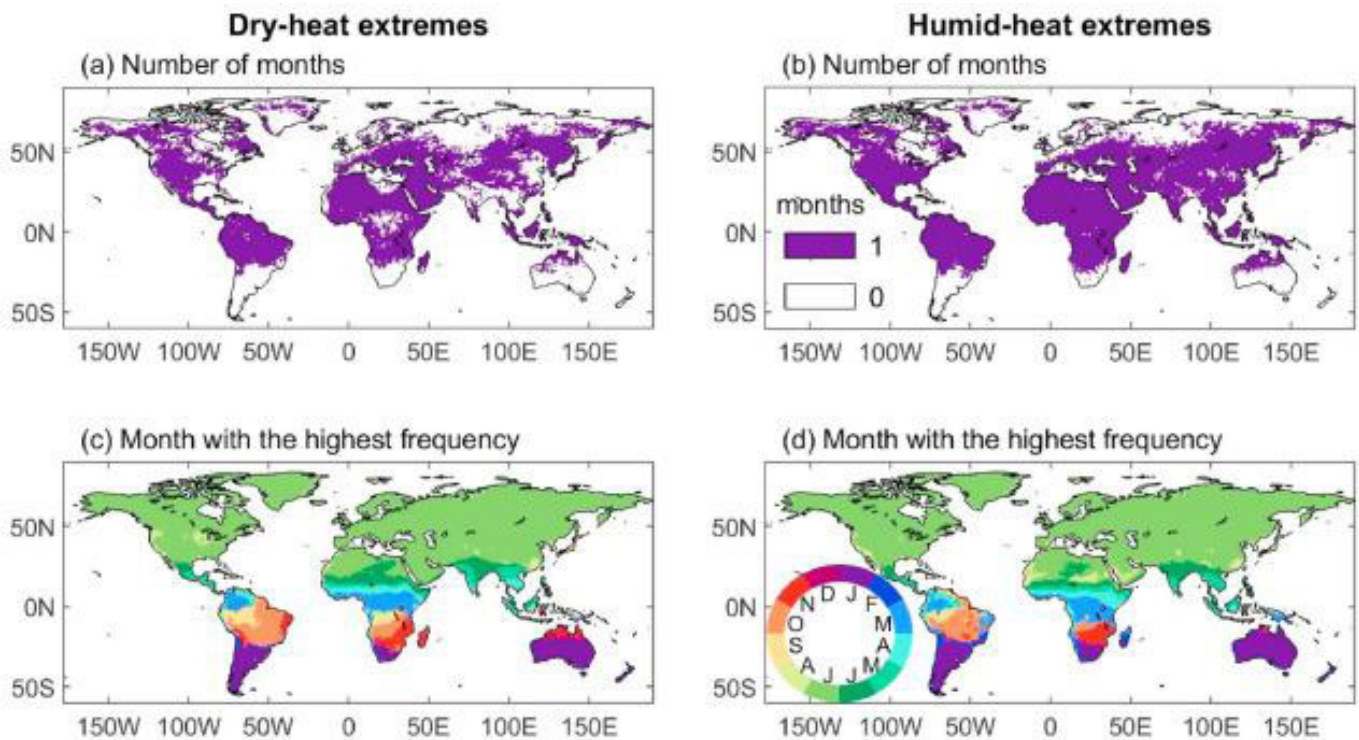
The three heatwaves surveyed here highlight some less obvious cascading consequences.

Power outages can affect the cold storage of foods in both homes and markets. They can also cause water pumps to fail, undermining both water supply and sanitation—at a critical moment of high demand. People living in tall buildings can be particularly affected both by the higher temperatures experienced on top floors and by the failure of pumps to deliver water. Disruptions in the supply and distribution of water can also undermine efforts to cool critical infrastructure, such as to prevent bridges from buckling in the extreme temperatures.

The Brazil heatwave illustrates the impact of these events becoming compounded by other hazards occurring simultaneously or in close succession. The dengue outbreak was likely to have been made worse by the earlier extreme heat and humidity. During the second heatwave, the total number of deaths from both the heat and the dengue outbreak could have been higher than if either had happened independently. Similarly, fatalities might have increased significantly during the heatwave in Sao Paulo had the massive, long-lasting power outage affecting 4 million of its residents occurred just three weeks later.

Some interesting differences between moist and dry heatwaves also emerge from examining these three events. First, heatwaves occurring on a large geographical scale can be both dry and moist. The 2015 Indian heatwave was predominantly a dry event, but high humidity in coastal locations resulted in exceptionally high HI levels in those locations. One would expect that river valleys and heavily irrigated areas could also generate significant moisture during otherwise dry regional heatwaves. Research has found that extreme dry- and humid-heat days often occur in the same month in mid to high latitudes and that, in tropical areas, humid- and dry-heat extremes can occur concurrently within a single month (Figure 2).⁹⁸

Figure 2: Seasonal characteristics of heat extremes for the recent historical period (1995 to 2014)



Note: Based on the CMIP6 multi-model ensemble mean: number of months with at least five extreme-heat days (a, b), and month with the highest frequency of days with a heat extreme (c, d).

Source: Xuewei Fan et al., 'Comparative assessment of dry- and humid-heat extremes in a warming climate: frequency, intensity, and seasonal timing', *Weather and Climate Extremes*, September 2024, 45:1–10, [online](#).

Dry and humid heatwaves have several different societal impacts. For example, dry heatwaves decrease the productivity of some crops more significantly than do moist heatwaves, but the latter can reduce the capacity of farmers to work in their fields, resulting in possibly equally harmful impacts. Extreme heat combined with high humidity also increases the sterility of rice plants and accelerates rice spoilage during storage, transportation and distribution.⁹⁹ This is a particular challenge in countries such as India, given its reliance on rice—a labour-intensive crop that involves the greatest exposure to dangerous humid heat.¹⁰⁰ About three-quarters of India’s workforce is in ‘heat-exposed’ sectors such as agriculture, construction, fisheries, tourism and forestry, which contribute approximately half of the country’s GDP.¹⁰¹

It’s encouraging that some places that have recently experienced deadly humid heatwaves have taken steps to reduce their exposure and vulnerability to future hazards. Following the 1995 disaster, Chicago implemented several measures to improve its resilience, including implementing a new heat warning system and emergency-response plans, establishing cooling centres and community outreach to at-risk groups.¹⁰² It seems likely that the relatively fewer fatalities it experienced in the subsequent heatwave four years later were a consequence of those improvements.¹⁰³

Following the deadly 2015 heatwave, Karachi also took steps to improve its preparedness, among other things by setting up early-warning systems, establishing cooling centres and preparing water-distribution systems.¹⁰⁴ The improvements were probably significant in reducing the impacts of a heatwave that struck the city two years later.¹⁰⁵

Building greater resilience to future lethal-humidity events is becoming increasingly urgent because of climate change. Indeed, both the 2015 South Asia heatwave and the 2023 Brazilian heatwave have been linked directly to climate warming. Analysis suggests that climate change was responsible for a substantial increase in the heat indices observed in both India and Pakistan¹⁰⁶ and the primary driver of the extreme temperature intensification in the Brazil event.¹⁰⁷

The next section examines how global warming is rapidly accelerating the risk of humid-heat extremes and lethal humidity.

2. A new climate era: the escalating context for humid heatwaves

The historical examples in the previous section illustrate how humid heatwaves have already caused devastating impacts. Yet these events are now unfolding within a radically different global context. Climate change is contributing to fundamental shifts in the Earth system. Six defining truths and features, described below, distinguish this era, shaping what societies can expect from extreme events such as humid heatwaves:

1. We have already entered a new climate era.
2. There is no avoiding significant additional warming and severe human impacts.
3. The pace of change is accelerating.
4. Community resilience is eroding as climate hazards, once rare, become more frequent.
5. Climate impacts are triggered by the combination of both slow-onset and rapid-onset hazards.
6. Climate change is an intensifying systemic crisis that touches every sector, every society, everywhere, all at once.

We have already entered a new climate era

The first defining feature is that the planet is now warmer than it's been in at least 100,000 years.¹⁰⁸ To put that in perspective, the great pyramids were built about 4,000 years ago, the development of agriculture began about 12,000 years ago, and Neanderthals roamed Eurasia until about 40,000 years ago. The relatively mild, stable climate that persisted for over 10,000 years enabled the emergence of human civilisation.

There's no human precedent for the current climate, let alone for the climate anticipated in the decades ahead. At 3°C of warming, the planet will be warmer than it's been in *millions* of years. Although climate modelling is helping us to understand this future landscape, the uncertainty and risks remain enormous, making it perilous to predict how multiple extreme hazards, including lethal humidity, will interact to disrupt complex human systems. The past is no longer a reliable indicator of what lies ahead, and societies will need to plan for conditions with no historical analogue.

There is no avoiding significant additional warming and severe human impacts

Because of inertia in the climate system, even if every car and factory in the world immediately ceased producing greenhouse gases, the climate would continue to warm well beyond the 1.5°C lower target set in the Paris Agreement.¹⁰⁹ The warming we're experiencing today is largely the result of carbon dioxide released a decade or more ago. Like a heavily loaded train, the climate system takes time to slow even after the brakes are applied.

This highlights the imprudence of waiting until extreme climate impacts, such as large-scale lethal-humidity events, become more visible before taking decisive action to reduce greenhouse gases and build societal resilience.

The pace of change is accelerating

A third defining feature is the speed at which climate impacts are now unfolding. In the mid-20th century, the most extreme heat events were rare, but by 2001–2010 they had become 90 times more common, and exceptionally extreme heat events that were virtually impossible in the earlier period had become 1,000 times more frequent.¹¹⁰ Since then, the pace has only quickened: between 2012 and 2024 the rate of warming was nearly double that of the 1980s, contributing to a non-linear surge in extreme-heat events.¹¹¹

The same non-linear pattern applies to other hazards, such as sea-level rise. Even modest increases make coastlines far more vulnerable to flooding. In some cases, every additional 10 centimetres can roughly triple the likelihood of a given coastal flood.¹¹² With sea levels projected to rise by up to 30 centimetres by 2050, what were once century-scale floods could soon occur annually.¹¹³ Most concerning of all, climate tipping points could accelerate those processes dramatically.¹¹⁴

Community resilience is eroding as climate hazards, once rare, become more frequent

With climate-driven hazards becoming more frequent, severe and widespread, the likelihood of damaging consecutive and simultaneous disasters is increasing sharply. In Queensland, Australia, for example, almost two-thirds of local government areas have experienced three or more major disasters—floods, fires or storms—in the past three years; nearly one-third have experienced five or more.¹¹⁵ Communities are increasingly hit by new disasters before recovering from earlier ones in a pattern that steadily erodes resilience.

This is happening even in wealthy regions with large recovery budgets; in developing countries, where resources are far more limited, recovery gaps are devastating. For populations exposed to extreme humid heat, overlapping crises will compound vulnerability and weaken the capacity to survive the next event.

Climate impacts are triggered by the combination of both slow-onset and rapid-onset hazards

Natural hazards can be slow-onset, such as drought and sea-level rise, or sudden-onset, such as cyclones, floods and bushfires. Increasing temperature is already affecting agriculture, while sea-level rise is eroding coastlines and contributing to saltwater intrusion. Those processes are intricately connected: drought can set the stage for bushfires, and sea-level rise can exacerbate flooding from storm surges.

Climate change is intensifying both slow-onset and rapid-onset hazards, and their interactions are increasingly visible. Many scientists believe that climate change is disrupting the jet stream¹¹⁶ and amplifying El Niño¹¹⁷ and La Niña cycles, helping to explain why multiple extreme disasters now strike across continents simultaneously. Alterations to the jet stream in 2010, for example, contributed to concurrent disasters across the Northern Hemisphere, while similar events in 2018 caused record heatwaves, droughts and deadly floods from Japan to California. The risk of those compound hazards is rising rapidly.

Climate change is an intensifying systemic crisis that touches every sector, every society, everywhere, all at once

Climate change is much more than an environmental crisis. It's a global systemic crisis, the disruptions of which are transforming the geopolitical landscape. Its systemic nature is often underappreciated because such complex interactions are extremely difficult to model.

Until relatively recently, because of that complexity, much of the scientific literature has examined hazards as independent variables rather than as interlocking stressors that interact across human and natural systems. Rising temperatures, humidity, floods, droughts, fires, pests and migration pressures are converging, often simultaneously. Understanding discrete extremes like humid heatwaves now requires analysing those wider connections: the compounding effects and cascading feedbacks that are defining the new climate-amplified risk landscape.

Humid heatwaves and climate change

Within this new era of accelerating and interconnected hazards, humid-heat extremes and lethal humidity stand out as among the least understood threats.

The United Nations' Intergovernmental Panel on Climate Change (IPCC) is the authoritative international scientific body for assessing the science related to climate change. It extensively addressed heatwaves in its most recent assessment, concluding that:

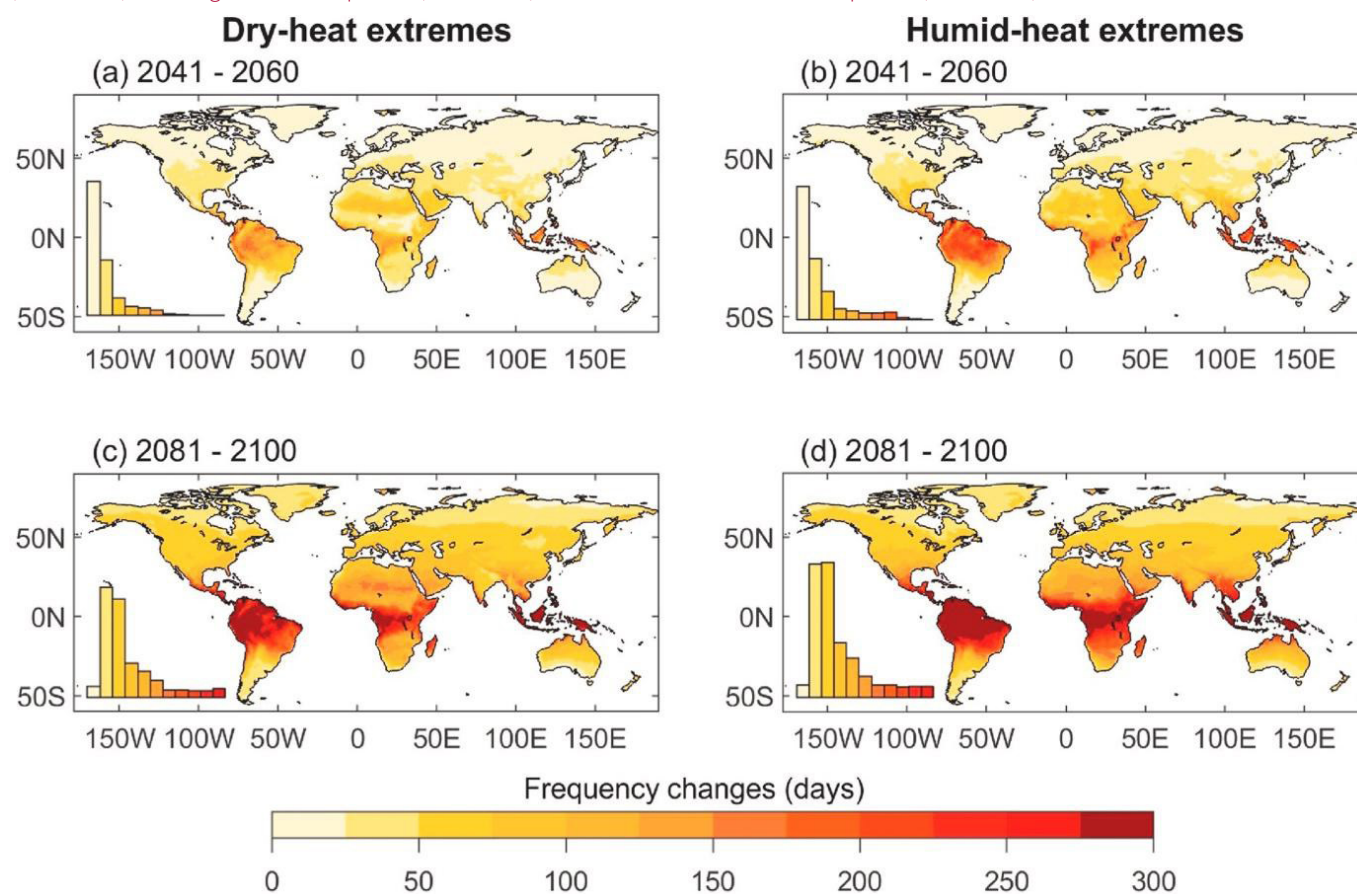
... it is *virtually certain* that further increases in the intensity and frequency of hot extremes, and decreases in the intensity and frequency of cold extremes, will occur throughout the 21st century and around the world. It is *virtually certain* that the number of hot days and hot nights and the length, frequency, and/or intensity of warm spells or heatwaves compared to 1995–2014 will increase over most land areas. The probability of temperature extremes generally increases nonlinearly with increasing global warming levels (*high confidence*).¹¹⁸

Research suggests that the hottest heatwaves are already lasting longer and occurring at a rate faster than temperatures are increasing.¹¹⁹ Regions such as equatorial Africa, South America and Southeast Asia are especially vulnerable, and events once considered rare are expected to occur dozens of times more often. For example, 35-day heatwaves in equatorial Africa could be around 60 times more frequent in the 2020–2044 period relative to 1990–2014.

The IPCC assessment applies to both dry and humid heatwaves. Indeed, the evidence suggests that, over the past four decades, the global population has become exposed to humid heat at a *faster rate* than to dry heat.¹²⁰ Observations since 1979 document that on average each person has experienced about five additional days of extreme humid heat per decade.¹²¹

Most concerning is that climate modelling under both moderate and high emissions scenarios shows rapid increases in those deadly events and rapid and large increases in exposed populations. Projections for 2041–2060 suggest a global average increase of about 35 extreme humid-heat days, but with tropical regions experiencing a 150-day increase in those events (Figure 3).¹²²

Figure 3: Spatial patterns of changes for frequency of dry-heat (a, c) and humid-heat (b, d) extremes in the mid-term future period (2041–2060) and long-term future period (2081–2100) relative to the recent historical period (1995–2014) under the SSP5-8.5 scenario



Note: The histogram at the bottom left in each subplot shows the distribution of changes in heat-extreme frequency for all grid cells globally.

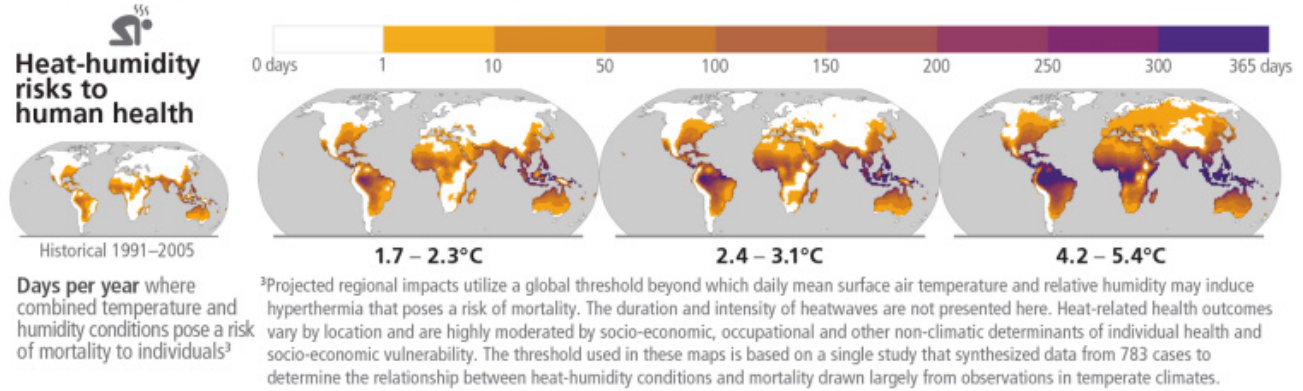
Source: Xuewei Fan et al, 'Comparative assessment of dry- and humid-heat extremes in a warming climate: frequency, intensity, and seasonal timing', *Weather and Climate Extremes*, September 2024, 45:1–10, [online](#).

Similarly, the latest IPCC assessment highlights the rapid increase of heat-humidity risk at different levels of warming (Figure 4).

Figure 4: Projected impacts

Future climate change is projected to increase the severity of impacts across natural and human systems and will increase regional differences

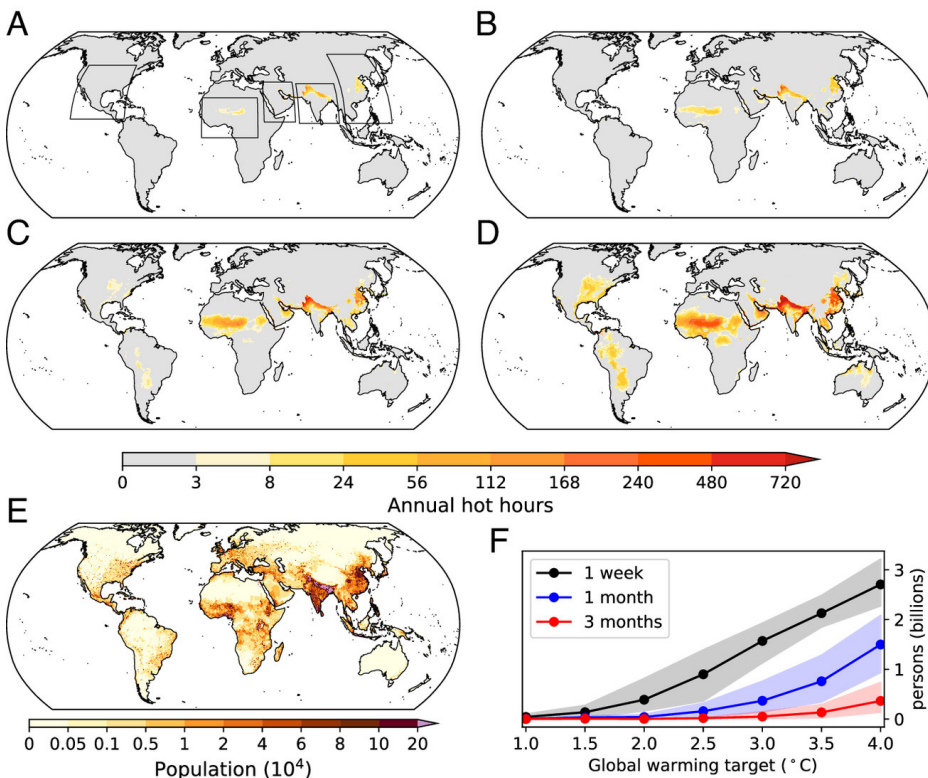
Examples of impacts without additional adaptation



Source: AR6 synthesis report: *Climate Change 2023*, IPCC, Figure SPM.3b.

Additional analysis also suggests that the number of present-day extreme wet-bulb temperatures will increase 150- to 250-fold by 2080.¹²³ In a pessimistic scenario in which the climate has warmed by 4°C by the end of this century, 2.7 billion people could be exposed to one week of daytime (8 hours) uncompensable heat stress (where all cooling mechanisms are insufficient and core body temperature begins to rise uncontrollably), 1.5 billion for a month, and more than 360 million people for an entire season (3 months) (Figure 5).¹²⁴

Figure 5: Annual hot-hours under (A) 1.5, (B) 2, (C) 3, and (D) 4 °C of warming relative to preindustrial level, (E) population projection in 2050 following the Shared Socioeconomic Pathway 2, and (F) population subject to accumulated duration of 1 wk to 3 mo of uncompensable heat stress annually under 1–4 °C of global warming (the shaded area corresponds to the 10th to 90th percentiles of CMIP6 model spread). Rectangles in panel a delineate regions where heat exposure increases with global warming are particularly large.

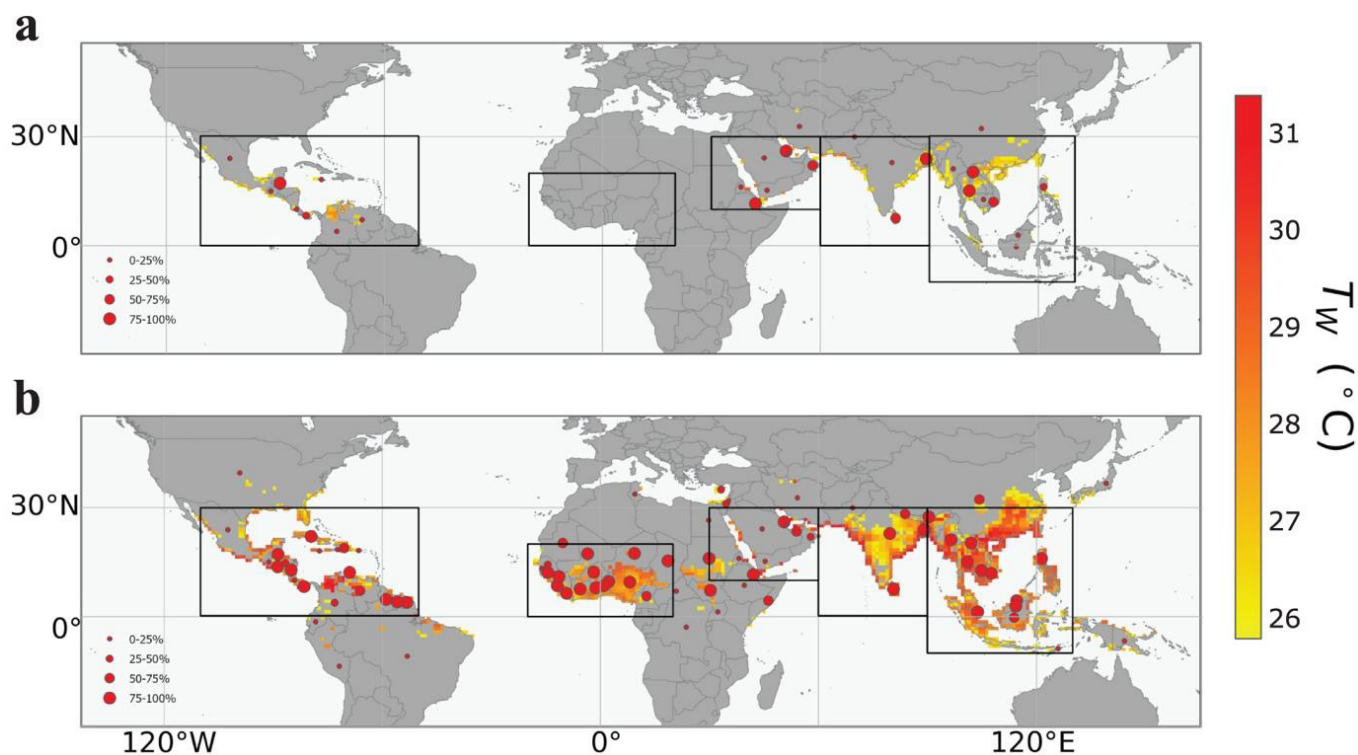


Source: Daniel J Vecellio et al., 'Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance', *PNAS*, 2023, 120(42):1-9, [online](#).

Tropical regions are projected to be particularly exposed.¹²⁵ By the late 21st century, populations in the tropics may experience extreme heat events, particularly extreme humid-heat days, for up to two-thirds of the year. The IPCC noted in its *Sixth assessment report* that, by that time, 50% to 75% of the global population could be exposed to life-threatening climatic conditions due to extreme heat and humidity.¹²⁶

Hundreds of millions of family farmers in the tropics and beyond will be highly imperilled by those extreme humid-heat events. City-dwellers, particularly in coastal equatorial areas, will also be at very high risk. Simulations indicate that, before the end of the century, about 45% of the projected global urban population (over 3 billion people) will be living in urban areas exposed to high humid-heat stress (Figure 6).¹²⁷

Figure 6: Present and future urban population exposure to high humid-heat stress



Notes: Colours indicate the decadal mean JJA urban T_w . Note that values of $T_w < 26^\circ\text{C}$ aren't shown here. Circle size indicates percentage of the urban population, by country, exposed to decadal mean JJA urban $T_w > 26^\circ\text{C}$ averaged over (a) 2000–2009 and (b) 2091–2100.

Source: Joyce Yang et al., 'Large humidity effects on urban heat exposure and cooling challenges under climate change', *Environmental Research Letters*, March 2023, 18(4), [online](#).

Five regional urban hotspots emerge from this analysis: in Central America/Caribbean, Western Africa, the Middle East, South Asia and Southeast Asia. Much of China is affected, and the results of other studies suggest that some of the country's largest cities face exceptional risk:

Many urban population centers in eastern China are expected to frequently experience the extreme heat-humidity events featured by the $T_{w_{\max}}$ well beyond the lethal humidity threshold of 35°C by the end of this century under [the] SSP5-8.5 scenario. For example, in Beijing, Shanghai, Guangzhou, and Chongqing, which are super cities in China, the $T_{w_{\max}}$ reaches and exceeds the survivability threshold frequently in the future. In these locations, the threshold of the 1-in-20-year annual $T_{w_{\max}}$ event in the current climate, for instance, is also projected to increase by at least 5.0°C under SSP5-8.5 and at least 3.0°C under SSP2-4.5, implying significant increases in risk levels of such extremes.¹²⁸

Catastrophic impacts are likely at thresholds far lower than 35°C T_w , and the duration of the exposure is a critical factor. Severe impacts in China may occur sooner, at significantly lower levels of warming. For example, analysis suggests that at 1.5°C of warming—a point that may be reached in only a few years¹²⁹—a heatwave as severe as China's worst on record (2013¹³⁰) would occur about once every three years, and, at 2°C of warming, every other year.¹³¹

Cascading impacts of humid heatwaves

As the surveys of historical humid heatwaves in Section 1 demonstrate, the human toll of those events extends well beyond those directly exposed and vulnerable. Humid heatwaves generate both immediate and cascading impacts that ripple through societies. For example, the surge in electricity demand for cooling can overload power systems and trigger blackouts. When electricity fails, so too can water pumps and refrigeration, disrupting water supply, sanitation, food storage and access to medicines. Power outages can also halt public transportation, stranding passengers, while water shortages make it harder to cool critical infrastructure, such as to prevent bridges from buckling in the extreme temperatures.

A recent extensive review of the research literature documented how North American heatwaves have triggered a chain of catastrophic events involving not only thousands of deaths, but also significant population displacement, flooding (from rapidly melting snow), wildfires, hazardous air quality and landslides (from permafrost melting).¹³²

The same review identified 11 thematic pathways grouped under three impact ‘clusters’ (social, economic and environmental) by which heatwaves can harm human and environmental systems. The pathways range from impacts in areas such as health, energy and infrastructure to labour productivity and marine life.

The review didn’t distinguish between moist and dry heat impacts, and not all the impacts areas are associated with humid heatwaves. *Particulate air pollution*, for example, is generally connected to dry heatwaves that contribute to the outbreak and spread of wildfires.

A useful area of future analysis would be to examine how the impacts, specific effects and mitigation strategies identified in the literature survey would differ if applied exclusively to humid heatwaves. For example, although crop yield losses are primarily associated with episodes of extreme dry heat, the reduction in labour capacity associated with humid-heat extremes could be just as impactful on crops in many regions and require unique mitigation strategies.¹³³

Humid heatwave interactions with other climate-driven hazards

Understanding the direct impacts of humid heatwaves and how they can cause harmful cascading secondary impacts is an important, but insufficient, step in grasping the true extent of the risk and how rapidly it’s accelerating. Climate change is not only increasing temperature and humidity but is also amplifying other hazards that will interact with heatwaves, compounding the societal impacts. The IPCC has identified this as a major risk:

Climate change impacts and risks are becoming increasingly complex and more difficult to manage. Multiple climate hazards will occur simultaneously, and multiple climatic and non-climatic risks will interact, resulting in compounding overall risk and risks cascading across sectors and regions . . . Concurrent and repeated climate hazards occur in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (high confidence). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (high confidence) . . . Future sea-level rise combined with storm surge and heavy rainfall will increase compound flood risks (high confidence). Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (high confidence). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (high confidence) . . . Adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (high confidence).¹³⁴

More recent research has modelled future changes in the compound occurrence of hazards linked to climate extremes.¹³⁵ It finds a major change is underway:

As we move from the present-day climate to a medium-high emission pathway, many regions in the world transition from primarily experiencing individual hazard/impact occurrences to routinely experiencing compound occurrences. This shift is chiefly associated with hazard/impact pairs including heatwaves, though other pairs such as crop failures and wildfires also rapidly grow in importance.

It moreover points out that while, presently, compound events rarely occur in back-to-back years at the same location, in future it will become common for some places to experience periods lasting a decade or more in which specific compound events happen at least once every year.

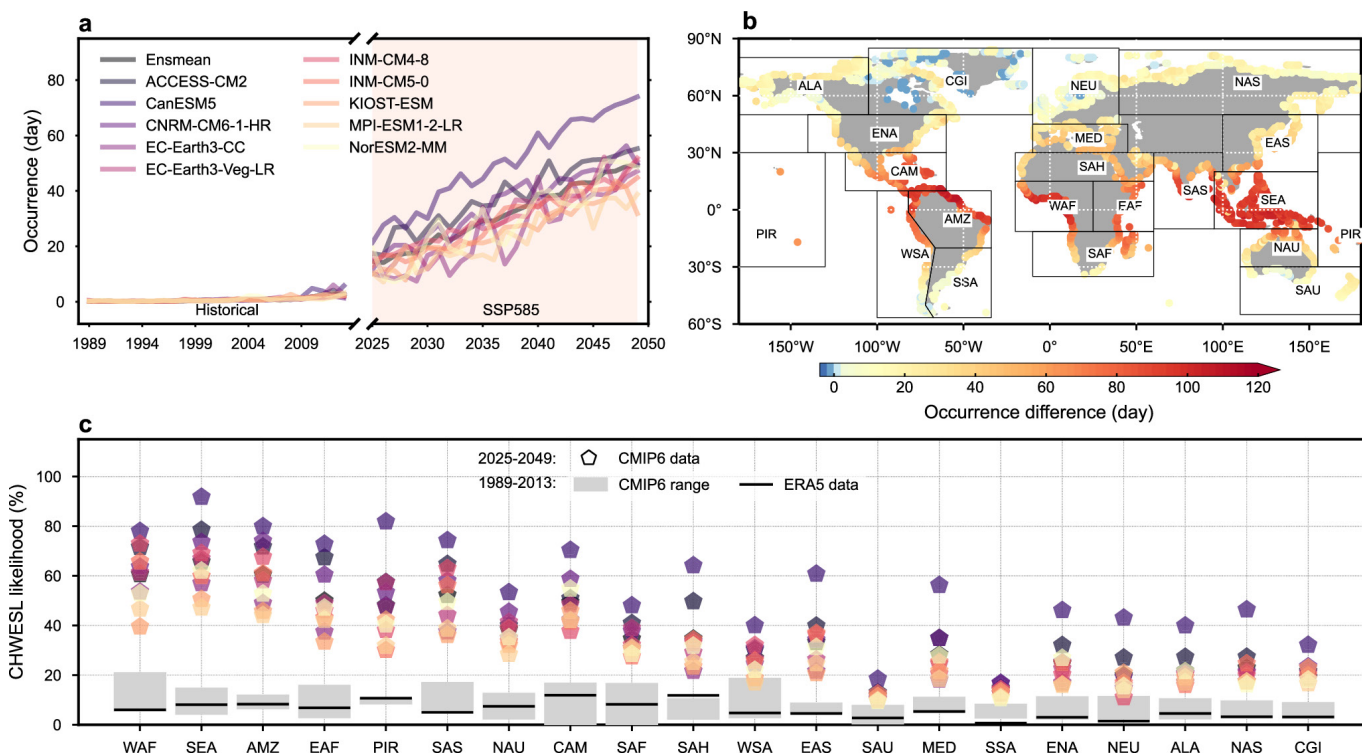
Other research suggests that, by mid-century, medium and high-latitude regions will not only experience more frequent and intense dry and humid heatwaves, but also that both will often peak in the same month.¹³⁶ Communities still reeling from one type of heatwave may be struck by the other, with impacts greater than the sum of the parts. For tropical regions, the peak occurrences may be separated by only one or two months.

Studies have also identified a connection between the occurrence of humid heatwaves and intense rainfall,¹³⁷ with the latter often immediately preceding or following the former.¹³⁸ Researchers found that the pairing of those two hazards has increased significantly in most regions globally over the past three decades. In the central US, for example, a high percentage of floods tend to be preceded by heatwaves.¹³⁹ And Japan’s devastating flood in 2018 was followed by unprecedented heatwaves a week later.¹⁴⁰ The compounding impact of those hazards varies depending, among other things, on the sequence in which they occur. For example:

when heat precedes, the soil becomes parched, hindering water absorption and resulting in flash floods during subsequent rainfall. Conversely, when heavy rainfall occurs first, it damages infrastructure, making it challenging to cope with subsequent heatwaves.¹⁴¹

Scientists have also documented a significant increase in the *simultaneous* occurrence of humid heatwaves and extreme sea levels, with a growing potential for enormous compounding societal impacts, particularly in lower-latitude coastal regions already exposed to storm surges and coastal flooding.¹⁴² More than 1.3 billion people live on tropical coasts, predominantly in less developed countries.¹⁴³ Research projects that by 2025–2049 climate change will have increased the likelihood of those hazards occurring simultaneously fivefold globally (from 7 days on average each year during 1989–2013 to 38 days) and eightfold in Southeast Asia (Figure 7).

Figure 7: Projected changes in the characteristics of concurrent heatwaves and extreme sea levels



- Occurrence (day) of concurrent heatwaves and extreme sea level (CHWESL) events during the future period of 2025–2049 and the historical period of 1989–2013 based on 10 CMIP6 simulation models.
- Average differences in the CHWESL occurrence (day) between the future period (2025–2049) and the historical period (1989–2013) across 10 CMIP6 simulation models. For each simulation model, the statistical significance of the difference is estimated by Student’s t test at a 95% confidence level. Only grid cells that exhibit a significant difference across all 10 CMIP6 simulation models are included in the change analysis.
- Likelihood of CHWESL events for each coastal region during the historical and future periods. The stars represent the average likelihood of CHWESL events during the future period in each region. The 10 stars represent the 10 CMIP6 simulation models. The grey shading illustrates the 95% uncertainty range of CMIP6 historical simulations. The lower and upper bounds of the grey shading represent the 2.5th and 97.5th percentile estimates of the likelihood of CHWESL events across the 10 CMIP6 models, respectively. The black line is the likelihood of CHWESL events identified based on ERA5 reanalysis data during the same historical period of 1989–2013. The order of coastal regions is determined by the average latitude of each region.

Source: Mo Zhou, Shuo Wang, ‘The risk of concurrent heatwaves and extreme sea levels along the global coastline is increasing’, *Communications Earth and Environment*, 2024, 5(144):4, [online](#).

The survey of the 2023 Brazil humid heatwave in Section 1 also showed that some events narrowly avoided overlapping with other hazards. For example, Brazil's record dengue fever outbreak was likely to have been worsened by the first of two humid heatwaves that struck that year. Had the timing been different, the second heatwave could have coincided with the outbreak's peak, potentially causing far more deaths and illness than either hazard would have produced alone. Similarly, fatalities in São Paulo could have risen sharply if the extreme storm that triggered the massive, long-lasting power outage affecting 4 million residents had occurred just three weeks later.

Such compound hazard events with cascading impacts are rapidly emerging in different parts of the world and on different geographical and temporal scales. A striking example of that was the 2010 atmospheric blocking event described earlier. In the first seven months of 2010, the Russian Federation experienced an unprecedented heatwave, which attribution analysis suggests was made five times more likely because of climatic warming.¹⁴⁴ The atmospheric blocking phenomenon over western Russia simultaneously affected the South Asian subtropical monsoon,¹⁴⁵ resulting in record flooding and a humanitarian disaster that affected 20 million Pakistanis.¹⁴⁶

In Russia, the extremely hot and dry weather helped trigger widespread wildfires, which destroyed 20% of the Russian wheat crop.¹⁴⁷ Fifty thousand people died from respiratory illness and heat stress. The drought struck not only Russia, but eastern China and Ukraine as well, causing major reductions in those regions' wheat harvests. During that period, very heavy rainfall in both Australia and Canada further diminished wheat harvests.¹⁴⁸ That combination of impacts contributed over the course of 2010 to a 40% increase in world food prices, which, in turn, led China to make a large-scale wheat purchase to secure its domestic supply and Russia to levy an export ban for the same reason.¹⁴⁹ That subsequently caused a spike in food prices in Egypt and elsewhere in North Africa, where it became a major factor in the Arab Spring.¹⁵⁰ Protesters in Tunisia brandished baguettes, while in Egypt they demanded 'bread, freedom and social justice'. By the end of 2011, governments in Tunisia, Egypt, Libya and Yemen had been swept away by popular revolts.

Australia's 2019–20 'Black Summer' is another example.¹⁵¹ That disaster involved multiple simultaneous, record-setting, climate-amplified hazards, directly affected close to 70% of Australians, and had major cascading consequences for the economy, biodiversity and public health. It also nearly triggered a major water-security crisis when the fires threatened Warragamba Dam, which is the source of 80% of Sydney's supply.

More recently, the 7.7 magnitude earthquake that struck Myanmar in March 2025, killing more than 3,600 people, highlights how the impact of geological hazards can become compounded by multiple, consecutive and simultaneous climate-related hazards. The earthquake survivors, their homes destroyed or severely damaged, and cut off from housing, electricity, water supply and sanitation, were forced to shelter in the open during April's extreme humid heat, when temperatures climbed above 40°C in many regions.¹⁵² Unseasonal heavy rains then compounded the crisis, damaging makeshift shelters, disrupting relief operations and heightening the risk of disease outbreaks. Communities in the south of the country—including Mandalay and Bago—that were severely affected by the earthquake were still recovering from unprecedented floods that had occurred less than six months earlier.¹⁵³

It's important to emphasise the hugely disproportionate impact that those rapidly accelerating climate hazards will have on less developed countries. Those countries generally have weaker institutions of governance, larger concentrations of marginalised populations, fewer resources to invest in reducing disaster risk and early warning and weaker social safety nets to support affected populations after hazards, such as humid heatwaves, strike. Consequently, it's not surprising that, to date, by far the most deaths from climate-related disasters have been in low- and lower-middle income countries.¹⁵⁴ For those states, disaster events have a significant impact on, or in some cases destroy, development gains built up over decades. Hurricane Ivan (2004), for example, cost Grenada over 200% of its GDP.¹⁵⁵

The following section takes a closer look at humid-heat risk, and how it may interact with other climate-amplified hazards, in Indonesia—one of the most geopolitically important and rapidly developing countries in the Indo-Pacific.

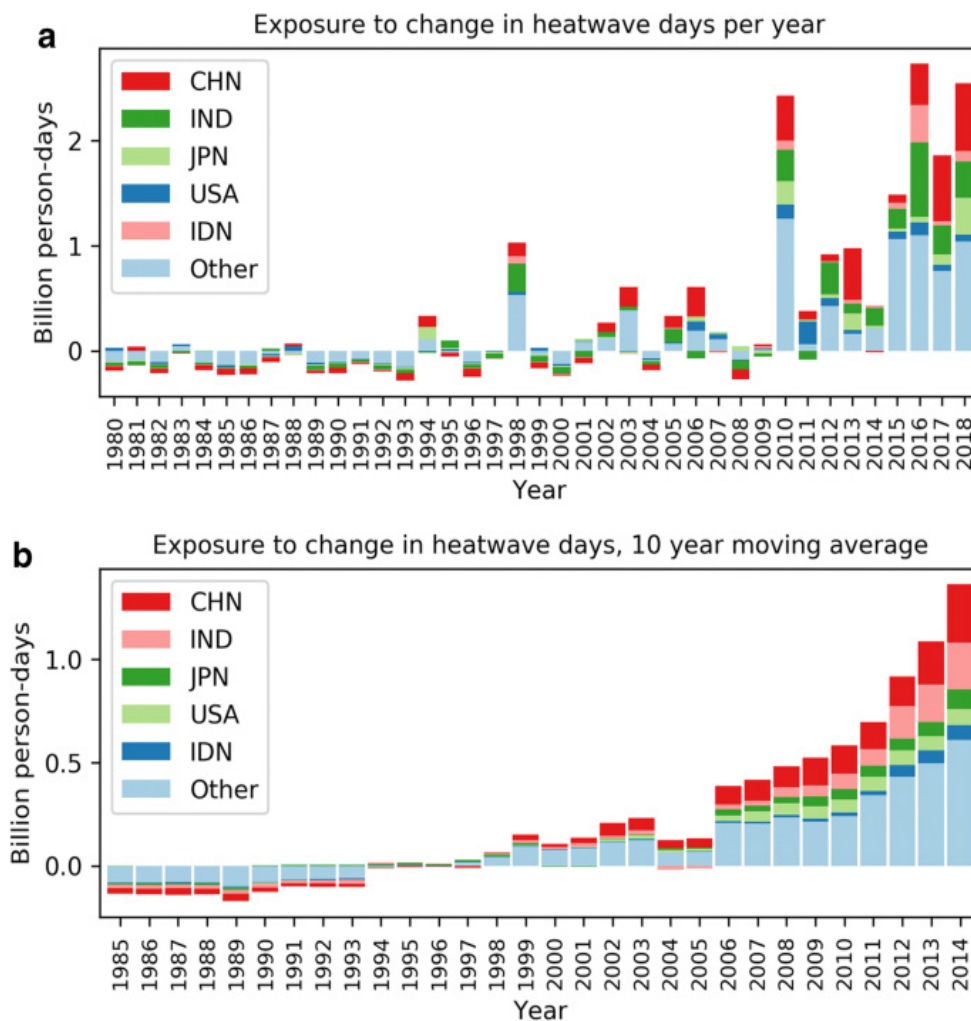
3. Indonesia: rising humid-heat and compound climate risks

As the previous section showed, humid-heat extremes are emerging as one of the most consequential effects of global warming. This section focuses on Indonesia, where humid-heat extremes will rapidly become a defining climate risk. While Indonesia has both a dry and a wet season, humidity remains high year round. Humid-heat extremes are increasing far faster than dry-heat events and will interact with other hazards, such as flooding, drought, sea-level rise and energy-system stress, creating major cascading societal impacts.¹⁵⁶

The 2025 *World risk report*, which assesses the disaster risk for 193 countries, determined that Indonesia has the third-highest risk globally (behind the Philippines and India).¹⁵⁷ The risk flows from a range of hazards, most prominently flooding and geological risk (earthquakes, landslides, volcanic eruptions and tsunamis contribute to more than 2,000 disasters every year).¹⁵⁸ But, as the climate continues to warm, humid-heat extremes will increasingly become a primary factor, including through interactions with other hazards.

Analysis suggests that by 2018 Indonesia had the fifth-highest total mean exposure of vulnerable people to heatwave days, behind China, India, Japan and the US.¹⁵⁹ Its rapid emergence in the top five exposed countries, as Figure 8 illustrates, occurred almost entirely within the preceding decade.

Figure 8: Exposure to change in number of heatwave days per year relative to the reference period



a Yearly.

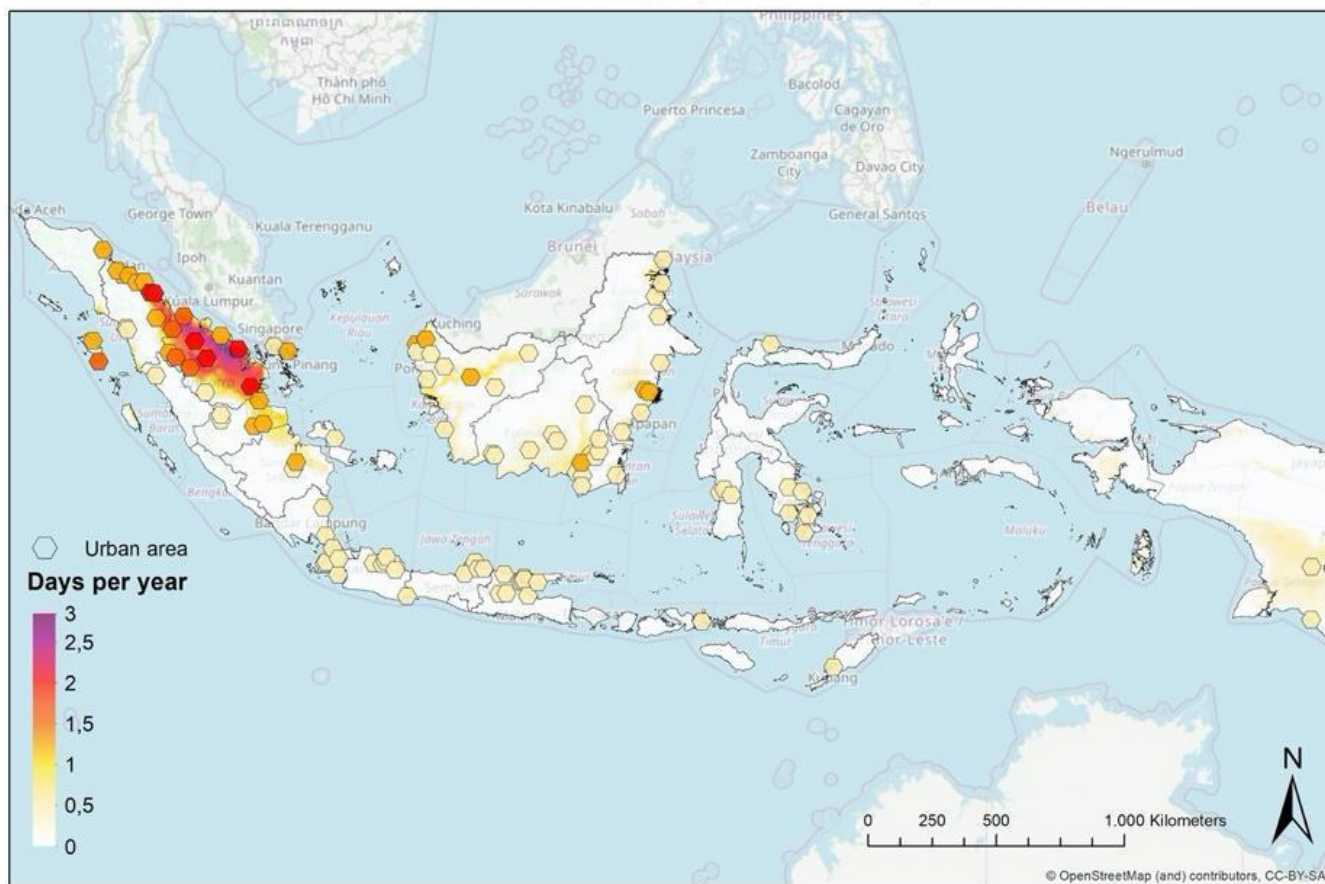
b 10-year centred moving average.

The top five countries by total exposure over the last decade are highlighted: China (CHN), India (IND), Japan (JPN), United States of America (USA), and Indonesia (IDN).

Source: Jonathan Chambers, 'Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018', *Climatic Change*, 2020, 163:539–558, [online](#).

There's only limited research on Indonesia's experience of humid-heat stress and its impacts. However, one recent study,¹⁶⁰ which drew upon high-resolution data for 110 Indonesian urban settlements, found that the country experienced on average 10 humid-hot days (WBGT_{max}¹⁶¹ >30°C) each year between 1983 and 2000, but with the average significantly higher (18 days per year) between 2000 and 2016 (Figure 9).

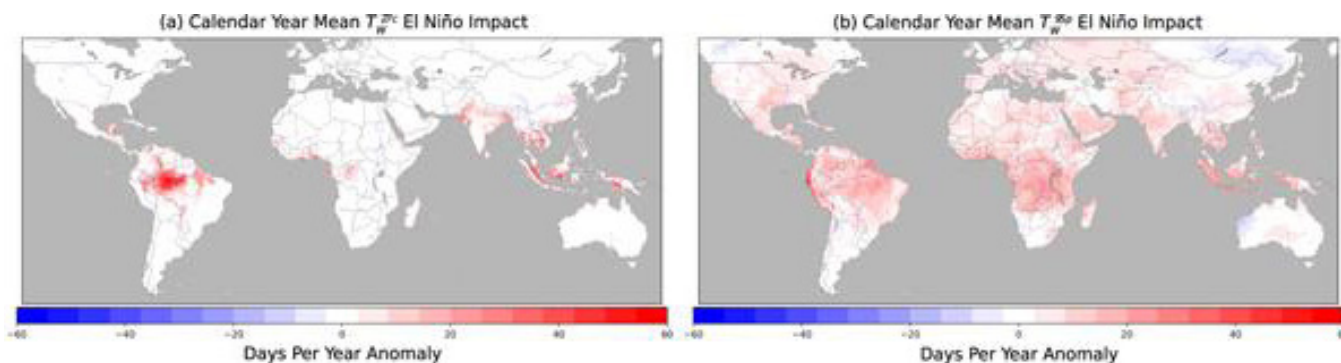
Figure 9: Annual increase in humid-hot days (WBGT >30°C), 1983 to 2016



Source: Carolina Pereira Marghidan, 'Research findings on heat stress in Indonesia', Red Cross and Red Crescent Climate Centre, February 2023, [online](#).

Implicit in these figures is the important role of El Niños (which, as the previous sections have highlighted, are likely to be increasing in severity as the climate continues to warm) in radically increasing the humid-heat risk.¹⁶² For example, during the El Niños in 1998 and 2016, which were among the most extreme on record, Indonesia recorded 50 and 57 humid-heat days, respectively (Figure 10).¹⁶³

Figure 10: Mean humid-heat frequency anomalies during El Niño events



Notes: Composites of the anomalous annual number of extreme humid-heat days for (a) and (b), during years with moderate to very strong ONI El Niño events (1983, 1987, 1988, 1992, 1995, 1998, 2003, 2010, and 2016). Composites are calculated after removing background linear trends in extreme humid-heat day frequencies. Composites are produced using data for the entire calendar year.

Source: Connor D Diaz et al., 'Increased extreme humid-heat hazard faced by agricultural workers', *Environmental Research Communications*, 2023, 5, [online](#).

Climate change is playing an increasingly important role in elevating humid-heat risk in Indonesia. A recent weather attribution assessment determined that, between May 2024 and May 2025 alone, it was responsible for an additional 99 days of extreme heat.¹⁶⁴

Several studies have examined how climate change is likely to amplify the humid-heat risks in Indonesia in the decades ahead. The 2025 World Bank *Climate risk country profile: Indonesia* summarised the scale of the risk. It noted that from 1995–2014 Indonesia experienced only about 2.5 days with a Heat Index >35°C. However, by 2040–2059, this number is projected to rise to 31.5 days (about a month). From 2051 to 2100, the number of days with a Heat Index >35°C is expected to increase by an average of 28.1 days (a month) *each decade*. According to the Bank:

By 2035, 17% of the population will be exposed to hazardous heat conditions, with the highest exposure in eastern and southern Sumatra and Kalimantan. By 2075, nearly the entire population in these areas will be affected. Overall, 71% of Indonesia will experience exposure, with most regions seeing at least 50% of their population affected.¹⁶⁵

Other analysis projects that, by 2080–2099, under a pessimistic climate scenario (RCP8.5), Indonesia may experience those extremely dangerous humid-heat conditions almost year round.¹⁶⁶

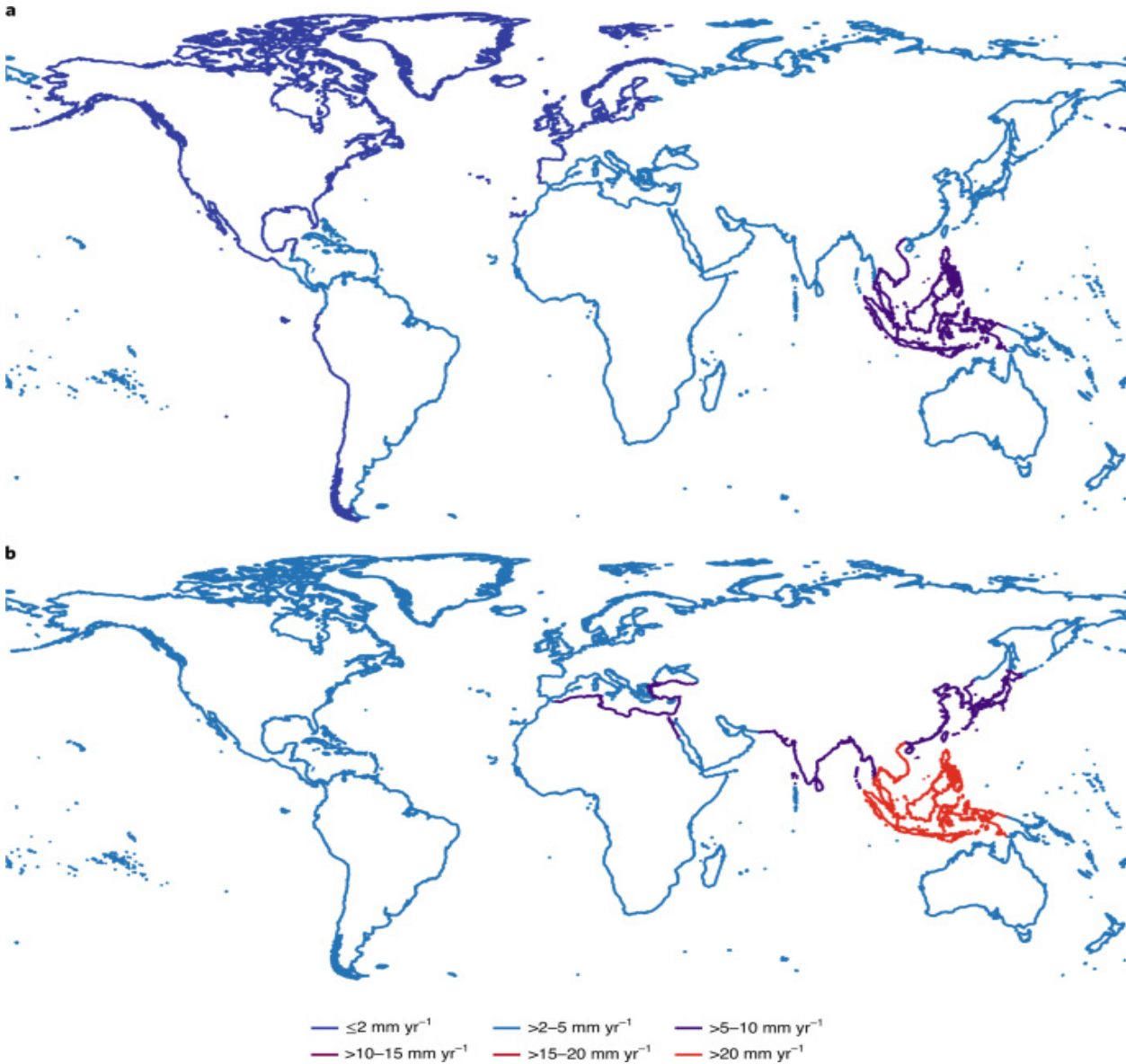
Compound hazards and cascading impacts in Indonesia

As Section 2 pointed out, humid and dry heatwaves have significant cascading societal impacts, including on human health and health systems, electricity supply (and, therefore, on water supply and refrigeration), infrastructure and agriculture. In a rapidly warming climate, they will moreover increasingly interact with other climate hazards, such as sea-level rise and increasing sea-surface temperature, more extreme precipitation and drought, greatly amplifying the overall societal impacts. Those other hazards are summarised briefly below.

Other climate-amplified hazards

Sea-levels are rising in Indonesia at four times the global mean relative rate (Figure 11).¹⁶⁷ Indeed, the country has among the fastest rate of sea-level rise in the world, in terms of both the length of coastline and the average coastal population affected.

Figure 11: Average relative sea-level rise rate for 23 coastal regions



Length-weighted (a) and population-weighted (b) average relative sea-level rise rate.

Source: Robert J Nicholls et al., ‘A global analysis of subsidence, relative sea-level change and coastal flood exposure’, *Nature Climate Change*, 2021, 11:338–342, [online](#).

Climate change is a central cause of that increase, but the increase is exacerbated significantly by groundwater depletion in coastal areas. Recent studies have also highlighted climate change’s role in increasing the frequency of *simultaneous* humid heatwaves and extreme sea levels and have determined that the risk is growing most rapidly in Southeast Asia, where Indonesia is singled out for its exceptional exposure and vulnerability.¹⁶⁸

Research further indicates that what were previously 1-in-100-year extreme sea level events may become *annual* occurrences in the country with just 1.5°C of global warming—a level that may be reached in less than five years.¹⁶⁹ The consequences for the approximately 20% of Indonesians who inhabit coastal zones will be profound. Between 2010 and 2021, Indonesia experienced 6.5 million displacements due to disasters, 4.1 million of which were associated with floods.¹⁷⁰ By the mid-2030s, the country’s population is projected to reach approximately 300 million. Most of that increase is expected to be concentrated in Java, particularly around Jakarta, which is highly flood prone.

Climate change is also contributing to multiplying marine heatwaves. Sea-surface temperatures were the highest on record in 2024. In the Southwest Pacific alone, nearly 40 million square kilometres was affected by marine heatwaves, which is over 10% of the global ocean surface area (roughly four times the size of Europe and of the US).¹⁷¹ Warming oceans are already contributing to sea-level rise, altering ocean currents and storm tracks and accelerating ocean acidification.¹⁷² Even existing levels of warming are having significant impacts on Indonesia, and the further warming projected over the next decades is likely to have severe consequences for the country.¹⁷³

The country is also increasingly likely to experience *extreme rainfall* in the decades ahead, and the resulting flooding will put at risk infrastructure, farmland and communities.¹⁷⁴ The frequency of flooding in Indonesia has been increasing steadily, particularly since 2010.¹⁷⁵ Indonesia's annual flood-induced damage in urban areas is projected to increase more than fourfold by 2030.¹⁷⁶ By 2070, it's estimated that 4 million Indonesians will be exposed to permanent flooding from sea-level rise. By 2075, 97% of the population is projected to be exposed to dangerous levels of extreme rainfall, with the highest exposure in Bali (79%), West Sumatra (75.5%) and West Sulawesi (64%).¹⁷⁷ The torrential flooding that affected Jakarta in early January 2020, the worst on record, was consistent with that trend.¹⁷⁸ It submerged over 60% of the city's residential areas, causing numerous deaths, more than 170,000 evacuations and \$700 million in damage.

Although the historical record of *drought* in Indonesia doesn't show a change nationally in the number of consecutive dry days, there's been a significant increase in consecutive dry days in the driest regions of the country (predominantly in the southern provinces), and that trend is expected to continue in a warming climate, with significant impacts on agriculture (see below) in those provinces, which is predominantly rain-fed on small-scale family farms.¹⁷⁹ Historically, droughts in Indonesia have tended to occur during El Niño years.¹⁸⁰

These increasing climate hazards will significantly amplify the impact of humidity–heat extremes. The vulnerability of two important sectors of Indonesia's economy, the power sector and agriculture sector, illustrates those connections.

Indonesia's power sector

A recent comprehensive survey of the climate vulnerability of Indonesia's power sector identifies many hazards that are already disrupting power supply and likely to do so increasingly in future.¹⁸¹ Not surprisingly, the survey found a strong link between rising heat and increased demand for electricity, which can trigger outages. Although over 90% of Indonesians are connected to the grid, power outages remain common; a major blackout in August 2019, for example, left more than 30 million people in Jakarta and surrounding areas without electricity for almost 24 hours.¹⁸²

But the survey also found a range of factors other than spikes in demand that may increasingly affect power generation, transmission and distribution,¹⁸³ including the following.

- **Heatwaves reduce gas power output**

Heatwaves pose a growing risk to natural-gas power plants. Gas turbines require dense ambient air for combustion, but hotter temperatures reduce air density, lowering combustion efficiency and cutting power output. That effect becomes more significant during prolonged heat periods, when consumer demand is already elevated.

- **Heavy rainfall disrupts distribution networks**

Intense rainfall is already a major trigger of distribution failures. Java and Bali alone have more than 22,000 kilometres of overhead distribution lines running through densely vegetated areas. During heavy rain, tree branches absorb water, sag, and disrupt conductors, causing short circuits and automatic shutdowns across distribution feeders.

- **Heavy rainfall reduces coal quality and generation efficiency**

Coal-fired power plants are also exposed to extreme rainfall. Many still rely on open coal yards, where stockpiles become waterlogged during storms. Wet coal burns less efficiently, reducing plant output and forcing operators to use more fuel for the same energy. In severe cases, runoff turns coal piles into sludge, clogging feeders and interrupting supply. Heavy rainfall also increases waste discharge into the sea, and marine debris can enter cooling systems, clogging pumps and condensers and forcing temporary shutdowns at coastal plants.

- **High winds damage power lines and delay fuel deliveries**

High winds are a major weather-related threat to distribution systems in the country. Winds topple trees, billboards and other debris onto overhead lines. Strong winds also affect fuel supply chains: when sea conditions deteriorate, coal-barge operations are suspended, delaying deliveries to coal-fired plants in the archipelago and reducing energy security.

- **Drought threatens hydropower**

Hydropower operators report that climate-driven shifts in rainfall patterns are already reducing reliability. Historically, years of extended drought—such as 1997, 2003, 2006 and 2011—forced hydropower plants such as Saguling and Cirata to operate at only 75%–87% of design capacity, resulting in tens of millions of dollars in losses. Increasingly erratic rainfall means reservoirs are harder to manage, increasing the risk of both energy shortfalls during droughts and spill events during extreme rains.

- **Sea-level rise and hotter sea temperatures threaten coastal power stations**

Coastal power stations depend on seawater for cooling. Higher sea temperatures reduce cooling efficiency, which leads to raised condenser pressure and lower generation output. At the same time, sea-level rise and tidal flooding threaten coastal electricity infrastructure. Some natural gas plants, such as in Priok and Tambak Lorok near Jakarta, sit just a few metres above sea level and experience regular tidal flooding during high tides and storms.

Any analysis of the vulnerability of Indonesian communities to future extreme humid-heat events that incorporates the risk of power failures from increasing demand for cooling must include the impacts of these other, rapidly accelerating, climate-related impacts on the grid, or else significantly underestimate the risks. Blackouts and rolling power shortages are increasingly likely to *co-occur* with deadly humid-heat events, greatly expanding the number of people requiring medical support, further overwhelming hospitals, interrupting water distribution and disrupting transport infrastructure.

Agriculture

As described in earlier sections, humid heatwaves have a significant impact on agriculture in many countries, and that's also true of Indonesia. The agriculture sector contributes about 13% of the country's GDP, and rice is the staple food for over 90% of Indonesians.¹⁸⁴ Twenty-nine per cent of total employment is in agriculture, highlighting the sector's significance to the national economy.¹⁸⁵ Moreover, small family-run farms, which are more vulnerable to extreme humid heat and other climate shocks, make up over 90% of the country's farming sector.¹⁸⁶

High temperatures combined with high humidity have been shown to increase the sterility of rice plants, depressing grain formation, and increased crop spoilage.¹⁸⁷ Studies have determined that the nation's rice production could decrease by 10%–25% with a 1°C increase in temperature.¹⁸⁸ Even just a few hours exposure to temperatures over 35°C can reduce the quantity and quality of rice crops.¹⁸⁹ Rice is also among the most labour-intensive crops, and rice croplands have experienced the greatest exposure to dangerous humid heat; that exposure is increasing rapidly.¹⁹⁰

With Indonesia's demand for rice projected to increase by about 30% over the next few decades, and rapidly accelerating exposure to extreme humid heat in its agricultural regions,¹⁹¹ the country's food security may be at risk, particularly given that its production and harvest of rice have decreased every year for the past seven years.¹⁹²

Other climate hazards, co-occurring with humid-heat extremes, will greatly amplify the impact on the agricultural sector. Rice is highly vulnerable to drought conditions, particularly during flowering and grain-filling stages.¹⁹³ As indicated above, Indonesia's southern provinces are at growing risk of drought. They're home to high concentrations of smallholder family farms that are particularly vulnerable because they rely on predictable rainfall and lack resources to invest in measures to reduce the impact of droughts.¹⁹⁴

Droughts have already had a major impact on Indonesia's agriculture. For example, between 2003 and 2008, they affected 17% of the country's 12 million hectares of rice under cultivation.¹⁹⁵ Climate-change-amplified El Niño – Southern Oscillation (ENSO) events will play a fundamental role in increasing the severity of drought. They're already the primary factor in the year-to-year variation in Indonesia's rice production.¹⁹⁶ Studies have also found that climate change is likely to increase the probability of a 30-day delay in the monsoon onset by 2050, with additional major consequences for the rice crop.¹⁹⁷

Extreme flooding will also have major impacts on Indonesia's agriculture. For example, between 2003 and 2008 the total rice area affected by floods equalled about 15% of the 2009 area under cultivation.¹⁹⁸ Evidence suggests that extreme flooding, with larger inundation areas and higher flood depth, will occur more frequently in future as the climate continues to warm, and that this would have significant consequences for Indonesia's rice crops.¹⁹⁹

Indonesia's exceptionally fast rate of sea-level rise will substantially exacerbate the impacts, as many rice fields are in coastal areas. On Java, for example, where the majority of Indonesia's rice is grown, 29% of the rice-growing areas are less than 10 kilometres from the coast.²⁰⁰ Those crops will be exposed both to sudden extreme floods—historically 1-in-100 year events that are transitioning to become annual events—and slow-onset impacts such as saltwater intrusion, which is a severe threat to food systems.²⁰¹ Up to 12 million hectares of Indonesia's land area is exposed to that risk.²⁰²

The collapse of Indonesia's coral reefs from warming seas,²⁰³ acidification and more severe weather—which is likely if temperatures increase by an additional 0.5°C (although some recent studies²⁰⁴ suggest that the tipping point for that collapse has already been reached)—will eliminate a major natural coastal defence against erosion, storm surges and flooding, further amplifying the impacts on crops.²⁰⁵

The demise of the reefs will have additional impacts on agriculture.²⁰⁶ Between 115 million and 160 million Indonesians reside near coasts and rely on marine resources for their livelihoods. The associated economic activity contributes up to 15% of the country's GDP. Moreover, 90% of Indonesia's fish stock, accounting for 60% of the average Indonesian's protein intake, is supplied by the coral reefs.

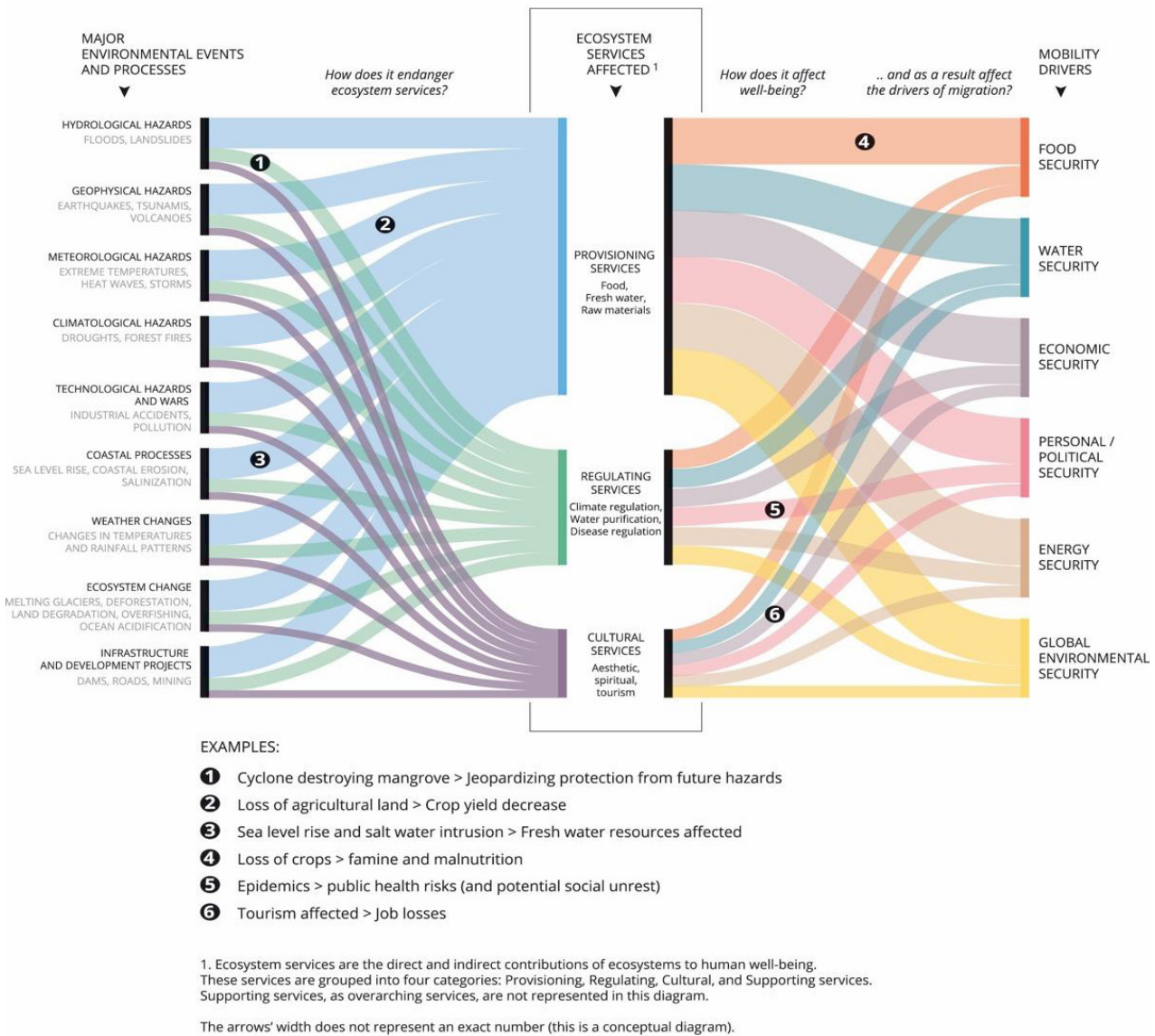
Without the reefs, many parts of Indonesia, including agricultural regions, will be more exposed and vulnerable to tsunami risk. The 2004 Indian Ocean tsunami, for example, had significant impacts on the sector.²⁰⁷ Some 92,000 farms and small enterprises were damaged or destroyed, 17,500 hectares of agricultural land was seriously damaged and thousands of hectares of land was lost to the sea. The tsunami also resulted in delays in planting caused by the need to rebuild dams and irrigation systems. Earthquakes, too, have major impacts on the sector: one study has determined that they're the third largest cause of disruptions to agriculture after floods and drought.²⁰⁸

Historically, Indonesia has relied on purchasing rice on the international market to fill any gaps in its own domestic supply. However, it's important to keep in mind that climate impacts of a similar kind will also affect Indonesia's neighbours and food-exporting countries in other regions. For example, a recent analysis found a 20-fold increase in the risk of simultaneous heatwaves in major crop-producing regions globally when particular disruptions to the Northern Hemisphere jet stream—which scientists are increasingly linking to climate change—are in place.²⁰⁹

Population displacement

These other climate and geological hazards will also play a growing role in displacing large populations, leaving them more exposed and vulnerable to humid-heat extremes. Indonesia has among the highest levels globally of population displacement from disasters. Numerous factors can determine displacement and mobility (Figure 12).

Figure 12: Ecosystem services: Relation to environmental change and impacts on mobility



Graphic produced by Zoi Environment Network, 2015. © IOM 2015.

This infographic has been produced with the assistance of the European Union. The contents of this infographic are the sole responsibility of IOM and can in no way be taken to reflect the views of the European Union or of IOM.

Source: Graphic produced by Zoi Environmental Network, 2015, with the assistance of the EU.

In the case of Indonesia, floods are the leading cause of population displacement (63% of the total), but earthquakes and volcanoes are also major factors, as are the other climate-related hazards described above. Some 4.2 million Indonesians were displaced by flooding between 2008 and 2021,²¹⁰ while geological hazards, alone, contribute to about 2,000 disasters on average each year.²¹¹ Those displacements are highly likely to accelerate in the future due to climate change:

Coastal inundation will drive population displacement, including as a result of undermining water and food security through direct impact as well as saltwater intrusion. Compounding those impacts is the expected collapse of coral reefs and, therefore, a lack of coastline-protecting structures. Relatedly, and as Indonesia's coastal communities rely on the availability of coral-dependent fish for food and trade, the collapse of coral reefs is likely to drive people to relocate further inland as they search for greater livelihood security. Although coastal-flood-driven displacement in Indonesia

is typically temporary, the frequency, severity and permanency of such displacement is expected to increase in line with the frequency and severity of disaster events. Assistance and support for those displaced is generally provided by extended family networks. However, with the increasing pervasiveness and concurrency of climate events and the increasing proportion of Indonesians subject to displacement, the ability of family networks to provide such support is likely to diminish.²¹²

Extreme climate-related events will increasingly coincide with geological hazards, compounding the scale of exposed populations. The 2004 earthquake and tsunami illustrate the extent of the risk. More than two years after the disaster, more than 460,000 Indonesians were still in refugee camps, temporary shelters and emergency tents,²¹³ which were characterised by extremely high indoor temperatures and humidity.²¹⁴

Modelling suggests that on average in any given year in the future 3.6 million Indonesians could be displaced by storm surges, riverine floods, earthquakes, cyclonic winds and tsunamis.²¹⁵

Population displacement across Indonesia illustrates how overlapping hazards are already reshaping lives and livelihoods. This growing risk highlights the need to rethink how we conceptualise 'disasters' such as humid-heat extremes and flooding. Those events can no longer be regarded as uncommon or seasonal shocks. In Indonesia and elsewhere, climate impacts are becoming increasingly simultaneous and consecutive rather than isolated. Humid-heat extremes, floods, droughts and coastal inundation will more often occur in overlapping sequences, striking before communities and systems have recovered. That pattern heightens vulnerability to extreme humid heat and compounds the cascading societal impacts that follow. With less time to recover between events, community resilience will erode rapidly, leaving people, infrastructure and governance systems weaker each year. Once rare, compound disasters are becoming a defining feature of the global risk landscape. In Indonesia, they'll be significantly amplified by humid-heat extremes.

4. From evidence to action: policy and research priorities for responding to lethal humidity

This report has surveyed how climate change amplifies humid-heat extremes, and how lethal humidity events, only recently emerging, are likely to occur increasingly across wider regions. It has also shown how other climate hazards will compound the societal impacts.

By the early 21st century, extreme-heat events had become 90 times more common than in the mid-20th century, while exceptionally severe events once considered extraordinarily rare were occurring 1,000 times more often. Since 2012, the pace of warming has nearly doubled compared with the 1980s, fuelling a non-linear rise in extreme heat. Humid heat is intensifying faster than dry heat across the most populated regions, exposing ever-growing numbers of people to dangerous thermal stress.

Parts of Southeast Asia and the Indo-Gangetic Basin now endure three or more months each year with wet-bulb temperatures exceeding 27°C, and the IPCC projects that, by the late 21st century, as much as 50%–75% of the global population could become exposed to deadly humid-heat extremes.

With that dire trajectory in mind, it's essential to address major gaps in our understanding of this hazard, communicate the risks effectively to policymakers and the public, and implement urgent measures to mitigate the impacts.

Laboratory and field research into the physiological, socio-economic and environmental impacts of humid heat on human health should be accelerated, including in several neglected areas. For example, it would be useful to improve our understanding of how livability²¹⁶ will be diminished as the survivability threshold is approached and to conduct additional epidemiological studies linking humid heat and mortality to further verify laboratory findings.

It's critical to expand and focus humid-heat research on less developed countries, not only to test the findings that have tended to draw upon experience in wealthier countries, but also because less developed countries, particularly in the tropics, are disproportionately exposed and vulnerable. The work should additionally help to strengthen domestic scientific and research capacity in those countries so that researchers can contribute more effectively to their national efforts.

Research on the impacts of warming on global labour productivity is also essential, as evidence suggests that humid heat is already responsible for annual labour losses comparable to those caused by the Covid-19 pandemic.²¹⁷ The existing economic impact is enormous and escalating rapidly, yet it's been largely neglected in policy circles and should be leveraged for far greater advocacy and policy impact.

As described in this report, humid heatwaves have significant cascading societal impacts. For example, spikes in electricity demand for cooling can trigger power blackouts that interrupt water treatment and supply, and disrupt public transportation, and that combination of effects increases the exposure of many more people to extreme humid heat. Even if climate change were not increasing the frequency, geographical scope, duration and intensity of humid-heat extremes, it will be essential to better understand where and under what circumstances those cascades occur, and how to interrupt or otherwise reduce their impacts. With climate change, however, identifying ways to mitigate such cascades becomes imperative.

Climate change also makes it critical to understand how lethal humidity interacts with other climate hazards that are also increasing in frequency and intensity, including dry heatwaves. Because climate change is expanding the geographical reach of heatwaves, it's also increasing the likelihood that humid and dry heatwaves will *coincide*. That was the case in the 2015 Indian heatwave, and research suggests that most tropical areas are already experiencing humid- and dry-heat extremes concurrently within a single month.

There's been a paucity of research on the compounding societal impacts of co-occurring humid and dry heatwaves in particular locations, or on how the scale and nature of those impacts will evolve in a rapidly warming climate. This is another important research gap that should be addressed. For example, as described earlier, humid- and dry-heat extremes can affect agriculture differently, raising the prospect that countries will need to plan for a much wider range of shocks and adaptation measures.

The report has also highlighted several ways in which lethal humidity can interact with other climate-amplified hazards. Identifying those connections and their resulting cascading societal impacts is immensely complex, but essential for understanding the true extent of the risk. Scientists have already documented a significant increase in the simultaneous occurrence of humid heatwaves and extreme sea levels, with a growing potential for enormous compounding impacts, particularly in low-latitude coastal regions already exposed to storm surges and coastal flooding, as well as a link between humid heat and extreme rainfall.²¹⁸

Similarly, the report has documented several ways other climate hazards could compound the impact of lethal humidity, including in the agriculture and power sectors, and how combinations of climate impacts can displace large populations, leaving them more exposed and vulnerable to humid-heat extremes.

Many countries, including those in the mid-latitudes, will be seriously affected by humid-heat extremes, but the impacts in the tropics are expected to be especially severe. In tropical regions, coastal cities—many of them megacities—are becoming key hotspots where lethal humidity coincides with other major climate hazards, affecting large urban populations.²¹⁹

By the end of this century, around 3 billion people are expected to live in tropical coastal cities facing high humid-heat stress. Those areas will also be exposed to rising sea levels, storm surges and severe flooding. Without major adaptation investments, the combined effects of urban heat islands, poverty and vulnerable informal settlements could have devastating social consequences. Cities such as Chennai, Manila and Dhaka already face multiple overlapping climate threats.²²⁰ They should become focal points for research, adaptation planning and investment in risk reduction.

China is geopolitically pivotal, yet its exceptional and rapidly growing exposure to humid heat, which poses significant risks to its future prosperity, has been largely overlooked by policy analysts. By the end of this century, extreme heat-humidity events with maximum wet-bulb temperatures above 35°C are projected to rise sharply across the country. Under a high emissions scenario (SSP5-8.5), roughly 80% of China's population may be exposed to humid heat exceeding the physiological limit of human survival.²²¹ It should be a priority for policy and security analysts, both within and outside China, to assess the consequences of this extraordinary risk for policy and planning.

One consistently overlooked factor will significantly increase lethal humidity impacts as the planet continues to warm: climate change is substantially reducing the time communities must have to recover from disasters. Humid-heat extremes, floods, droughts and coastal inundation will increasingly occur in overlapping sequences. With less time to recover between disasters, community resilience will erode rapidly, leaving people, infrastructure and governance systems weaker each year. It's vital for emergency-management and climate-adaptation planners to incorporate this more realistic understanding of resilience, rather than assuming recovery capabilities based on the outdated notion that disasters are rare or seasonal events.

Heat action plans (HAPs) are a key tool used by governments to reduce heatwave risks. They typically include early-warning systems, designated cooling centres, public-health and emergency-response components, and communication strategies. Not surprisingly, their quality varies. There are three main weaknesses.

The first is fundamental: relatively few HAPs integrate human physiology in the models used for warning systems,²²² and, relatedly, they often fail to include humidity in early-warning systems, communication strategies and other elements of planning and response.²²³ Those are dangerous omissions that need to be rectified, particularly given the dynamics of humid heat described in this report.

Second, many HAPs don't adequately address social inequalities and the needs of disadvantaged populations—the groups among the most exposed and vulnerable to humid heat.²²⁴

Third, HAPs generally focus on short-term emergency preparedness but far less on defining the longer term investments required (such as urban infrastructure improvements) and integrating climate-change projections into those investments.²²⁵

All three of those weaknesses should be addressed as a matter of priority.

There's a wide range of measures incorporated in HAPs²²⁶ and identified in the literature to reduce population exposure and vulnerability to humid heat.²²⁷ A comprehensive 'toolbox' of those measures, ranging from small-scale, low-tech initiatives to large-scale, more complex investments, should be developed and shared widely with national and subnational governments, international development banks, aid agencies and others. They would include actions such as the following.²²⁸

1. *Strengthening essential services*

- Expand and equip emergency health services to handle surges in heat-related illnesses.
- Ensure water and electricity systems can meet higher demand during heatwaves without failure.
- Maintain reliable and accessible transport systems during extreme heat events.
- Strengthen early-warning systems for heat alerts, ensuring broad coverage and timely communication.

2. *Social-protection and policy measures*

- Integrate cooling and energy needs into social-protection programs to help vulnerable households afford electricity for cooling.
- Pass and enforce worker safety laws that limit exposure and require adequate rest, hydration and shade.
- Include cooling considerations in labour policies and urban planning regulations.
- Legislate and enforce building codes that promote both passive (for example, insulation, ventilation) and active (such as air conditioning) cooling measures.

3. *Urban and infrastructure design*

- Design towns and cities with accessible cool spaces, green areas and water features for public relief.
- Increase urban greenery, shade trees and reflective or light-coloured surfaces to reduce the urban heat island effect.
- Create cooling shelters and stations for outdoor and vulnerable populations.

4. *Workplace and occupational adaptations*

- Shift work hours to cooler times of day (early mornings, evenings or nights).
- Introduce mandatory rest breaks and hydration intervals during heatwaves.
- Provide shaded rest areas and access to cool water for outdoor workers.
- Mechanise or automate the most labour-intensive tasks to reduce physical exertion in extreme heat.
- Offer heat safety education and training to workers and supervisors.

5. *Built environment modifications*

- Increase shading on building exteriors (for example, shutters, solar shades, awnings or trees).
- Improve ceiling and roof insulation to reduce indoor heat build-up.
- Apply reflective or 'cool roof' coatings (such as white paint) to lower indoor temperatures.

6. *Food and supply-chain resilience*

- Enhance cold-storage facilities to reduce heat-related losses in agriculture and food distribution.

7. *Community-level and collective actions*

- Expand public access to water, electricity and shaded areas.
- Promote community-based heat awareness and preparedness programs.

Of course, the direct or indirect objective in many such initiatives is to achieve *cooling*—and a primary way to do that is by ensuring the resilience of electricity grids. In the record-breaking extreme heat that struck Vietnam in 2023, thousands of Hanoi residents had to relocate to air-conditioned shopping malls due to power cuts, and city officials turned off streetlights to keep the national power system running.²²⁹

Research suggests that more than 1.1 billion people globally are already at high risk due to lack of access to cooling,²³⁰ and the International Energy Agency (IEA) projects that demand for cooling could more than double within the next 25 years.²³¹ By that point, nearly 2 billion people in hot countries will lack access to air conditioning.²³² It's therefore crucial to identify alternative cooling options that don't rely on centralised grids. As the IEA has observed, solar PV technologies are promising options:

Improvements in solar technologies, including lower costs, are offering new opportunities to make significant progress on electricity access in developing countries. Solar PV packs are a growing market for providing off-grid access. Expanding that access to include cooling services via an AC would require greater electricity generation and battery storage capacity. But it could potentially offer an affordable form of access to cooling for populations in hot countries.²³³

Given the billions of lives at risk and the enormous economic consequences, keeping people cool in a warming climate should be addressed as a *global grand challenge*. Existing cooling initiatives²³⁴ should be expanded, scaled up and resourced like other bold global initiatives in the health sector.²³⁵ Implementing numerous other interventions at the landscape, building (such as reflective roofing) and individual levels should be elements of the grand challenge.

There's solid evidence that investments in planning and preparing for lethal humidity events can reduce the risks. For example, the decline in deaths during Shanghai's 2003 heatwave is attributed largely to measures introduced after the 1998 event, including higher public awareness and the establishment of a heat warning system.²³⁶ This report's surveys of the risk-reduction measures implemented in the aftermath of recent extreme humid-heat events in Chicago and Karachi also demonstrate this.

Nevertheless, if the world warms by 2°C–3°C, or more, as now seems likely,²³⁷ it's clear that even these radically scaled-up initiatives will be inadequate to address the scale of societal impacts caused by lethal humidity, compounded by other climate-amplified hazards. The only option to prevent that bleak outcome is to reduce greenhouse gases emissions globally and rapidly. The Lethal Humidity Global Council has identified four key policy shifts urgently required to achieve that:

1. *Real zero emissions: complete replacement (phasing out) of fossil fuels with renewable energy.*
2. *Removal of barriers to green industry, including fossil-fuel subsidies, before 2030.*
3. *Matching of incentives and disincentives to risk with carbon pricing.*
4. *Economic stimulants to encourage green growth and transformation.*²³⁸

The stakes are enormous, and the window of opportunity to mitigate the climate impacts is closing. Governments, the private sector and civil society must act rapidly, decisively and purposefully to ensure that lethal humidity remains a rare occurrence, rather than a deadly reality for billions of people.

Appendix

Heatwaves and humid heat: definitions, mechanisms, human limits and meteorological processes

This appendix provides technical background on humid heat and the concept of lethal humidity. It describes how heatwaves are defined and measured and summarises recent literature on the critical role of humidity. It also highlights the broad range of other factors, including environmental and socio-economic factors, that influence human exposure and vulnerability to those extreme events. Additionally, it outlines the variety of meteorological conditions that give rise to humid-heat extremes and describes where they tend to occur.

Extreme heat is the deadliest²³⁹ of all natural hazards, yet it lacks a consistent definition. Establishing this is fundamental to analysis that grapples with the full scope of the threat.

While floods, cyclones and droughts are measured against well-established meteorological standards, ‘heatwaves’ are described in very different ways across countries, sectors and even scientific disciplines. Some refer to high humidity, while others don’t. Nevertheless, there are some common themes, as the following definitions of ‘heatwave’ suggest:

- *US National Weather Service*: A period of abnormally hot weather generally lasting more than two days. Heatwaves can occur with or without high humidity.
- *US National Oceanic and Atmospheric Administration (NOAA)*: A period of abnormally and uncomfortably hot and unusually humid weather. Typically, a heatwave lasts two or more days.
- *UK Met Office*: An extended period of hot weather relative to the expected conditions of the areas at that time of year, which may be accompanied by high humidity.
- *World Meteorological Organization*: A period where local excess heat accumulates over a sequence of unusually hot days and nights.
- *Australian Bureau of Meteorology*: A heatwave is when the maximum and minimum temperatures are unusually hot over three days. This is compared to the local climate and past weather.

A recent survey has pointed out that there’s a lack of consistency globally in the temperature thresholds, duration and number of days used to define heatwaves.²⁴⁰ One study identified 45 different definitions, most of which combine temperature indicators, thresholds and durations.²⁴¹

It isn’t surprising that countries apply different definitions. Heatwave thresholds vary according to local conditions, including topography, geography and the built environment. In the UK, for example, each *county* has a different official temperature threshold.²⁴² The diverse definitions of heatwaves reflect both varying standards and practice and the unique needs of different workplaces and environments (for example, underground mining versus outdoor agricultural work). They also reflect the wide range of reasons heatwaves are studied. For example:

Climate scientists, who are primarily interested in the evolving statistics of weather in climate change, tend towards definitions that include a probability of exceedance in some relatively straightforward metric, usually defined relative to a long-term mean. Health researchers, in contrast, are interested in the aspects of a heat wave that are most relevant to human well-being. These heat wave definitions are also more likely to be regionally specific than climate-focused definitions and may also target vulnerable subsets of the population.²⁴³

The Australian Bureau of Meteorology definition focuses on both unusually hot maximum and minimum temperatures, recognising that higher overnight temperatures lead to more rapid warming the following day, more hours of extreme heat, and less time for people to recover—a major²⁴⁴ challenge in Australia where very high night-time temperatures now occur 10% of the time (five times as often as just a few decades ago). Interestingly, the high overnight lows are probably linked to high water content in the air, although that isn’t explicitly mentioned.

Clearly, temperature, alone, is insufficient for measuring heat stress. Human heat-stress risk is determined by four environmental factors (temperature, humidity, wind speed and mean radiant temperature) and two personal parameters (activity and clothing).²⁴⁵

A fundamentally important environmental factor is humidity, which can lower the temperature at which severe human impacts emerge. As one prominent lethal-humidity expert has put it, ‘At the end of the day, if you can sweat, humidity is going to determine when heat stress is lethal.’²⁴⁶

Both dry- and humid-heat extremes occur globally, but they differ in where and when they occur, and their effects vary across sectors such as health, agriculture, water and ecosystems.²⁴⁷ Many definitions of ‘heatwave’ now incorporate ‘humidity’ in recognition of the critical role it plays in amplifying heat’s effects on the human body.

Under conditions of high temperature and humidity, the body’s main cooling mechanism—perspiration and evaporative heat loss—becomes insufficient because the air is already saturated with moisture. Prolonged exposure causes a dangerous rise in core body temperature. To compensate, the body redirects blood from internal organs to the skin to offload heat. A core problem is reduced oxygen supply to the gut. That lack of oxygen damages the gut lining, making it more permeable and allowing bacteria to pass into the bloodstream. The body responds with an intense, system-wide inflammatory reaction, which can trigger widespread coagulation and death. Those impacts can cascade, with the failure of one organ worsening others, leading to multiple organ failure and death. One study identified 27 distinct pathways through which such cascades can trigger organ failure.²⁴⁸

Additionally, because the body diverts large amounts of blood to the skin to help with cooling, the heart must work harder to maintain blood pressure. That increased cardiac workload, which is reflected in a much higher heart rate, raises the risk of a catastrophic cardiovascular event in people with underlying heart conditions, such as coronary artery disease.²⁴⁹

Heat combined with humidity is measured as the ‘wet-bulb temperature’ (T_w),²⁵⁰ which is the lowest temperature that air can reach through evaporative cooling. It provides a direct measure of how easily perspiration can evaporate and therefore how effectively the human body can cool itself. To determine T_w , a wet fabric is wrapped around the bulb of a thermometer and exposed to circulating air. At 40°C and 50% relative humidity, T_w is 31°C; at 40°C and 75% humidity, it’s about 36°C. At 100% humidity, the wet-bulb temperature equals the air temperature because no evaporation is possible.

Early research suggested that exposure to T_w of 35°C for extended periods marks the limit of human adaptability, as dissipating extreme heat becomes impossible.²⁵¹ The 35°C mark has since been widely used as the lethal-humidity threshold. This report’s discussion of ‘extreme humid heat’ refers to conditions that have relatively infrequently surpassed that threshold but will increasingly do so as the climate continues to warm.

Recent research has urged caution in applying the threshold, given that it assumes the exposed subject is young, healthy, sedentary, unclothed, shaded and of average size—conditions rarely met in the real world. Even in healthy young adults, newer studies²⁵² show that the threshold is lower:

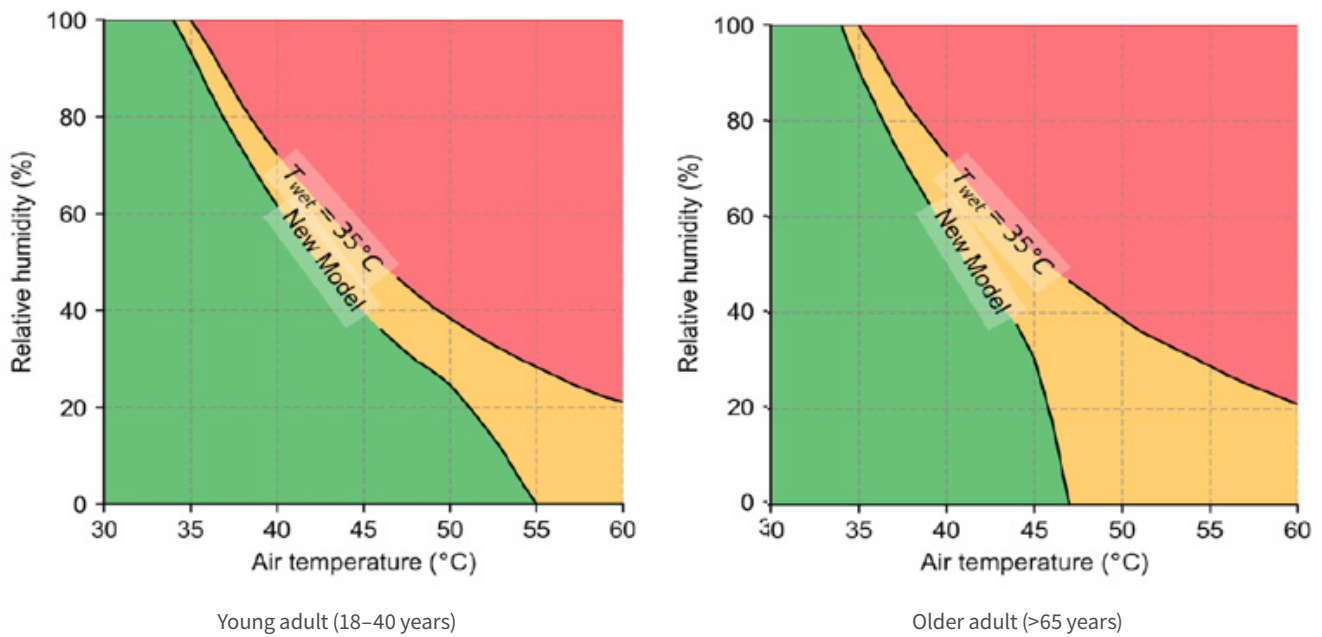
[O]nly recently have laboratory studies identified levels of humid heat above which core temperature cannot be held at a safe level for scenarios of minimal activity (for example, standing and talking). These ‘uncompensable thresholds’ differ substantially across ages, corresponding to wet-bulb temperatures of about 25°C to 31°C for younger adults . . .²⁵³

Figure 13²⁵⁴ illustrates the findings of one new model—which, unlike earlier ones, incorporates the limitations of human physiology—that the threshold for heat-death after six hours of exposure is reached well below the 35°C T_w for both young and older adults:

The Heat Index (HI)²⁵⁵ is often used for communicating to the public what the temperature feels like when relative humidity is combined with air temperature. Because the index’s values were devised for shady, light-wind conditions, it’s an effective measure for only a narrow range of real-world situations. In contrast, the wet-bulb global temperature (WBGT) is a more complex metric of heat stress designed for physically active populations outdoors in direct sunlight.²⁵⁶ It incorporates factors such as temperature, humidity, wind speed and solar radiation.

Extreme-heat indicators necessarily rely on simplifying assumptions, given the wide range of individual risk factors. Those include age, gender,²⁵⁷ body size,²⁵⁸ metabolic rate,²⁵⁹ mental health, comorbidities, medications²⁶⁰ and disabilities, as well as acclimatisation,²⁶¹ socio-economic status, dwelling type and access to air conditioning.

Figure 13: New Tw survivability limits for younger and older adults under shaded/indoor or sun-exposed conditions



Source: Jennifer Vanos, Gisel Guzman-Echavarria, Jane W. Baldwin, Coen Bongers, Kristie L. Ebi, and Ollie Jay, “A Physiological Approach for Assessing Human Survivability and Liveability to Heat in a Changing Climate,” *Nature Communications* 14, no. 7653 (2023): Article 7653, [online](#).

The evidence suggests that vulnerability to extreme heat is highest among elderly people with cardiopulmonary and other chronic disease.²⁶² Very young children and people over 65 account for most emergency-room visits and deaths during heatwaves.²⁶³ Ageing reduces blood flow to the skin and sweat gland output in response to heat stress, and older adults are more likely to have co-morbidities, such as cardiovascular disease. The upper limit of humid-heat tolerance in older adults is significantly lower than in younger individuals.²⁶⁴

However, important recent research on temperature extremes in Mexico,²⁶⁵ drawing on uniquely detailed data, including station-level wet-bulb temperature estimates, found that people under 35 years old suffered most humid-heat-related deaths. It suggests that the disproportionate impact reflects behaviour and occupational factors. Young adults are more likely to work outdoors with minimal flexibility for precautionary action. The analysis suggests that, in a warming climate, the mortality burden will grow to include young people as well as the elderly. The societal impact of that shift would be profound, given the economic productivity of younger adults.

Most research on heat stress comes from high- and middle-income countries, rather than developing ones. As one study observed, ‘In some locations (such as some Australian cities like Brisbane or US cities like Phoenix) there have been more studies on heat and morbidity conducted than on the entire continent of Africa.’²⁶⁶ Poverty amplifies vulnerability to heat stress, even in wealthy countries. During the 2003 French heatwave, mortality rates in poorer parts of Paris were twice as high as in the wealthier districts.²⁶⁷

More than 1 billion poor people live in highly exposed urban environments, and that has serious implications for their resilience to heatwaves.²⁶⁸ Houses in informal settlements are typically built from low-cost materials with poor ventilation and insulation. Air-conditioning ownership in low-income households is often below 10%, and typically less than 5% in informal settlements. Unreliable electricity and high costs further limit access to cooling, while evaporative cooling through sweating increases dehydration risk in communities already facing water scarcity. Thus, standard public-health advice—such as to drink water or shelter indoors—can be ineffective or even counterproductive where water insecurity, poor water quality and poor housing prevail.

Similarly, about two-thirds of the world’s 3 billion rural residents are smallholder farmers who tend to be poor, food insecure and highly exposed to heat and other hazards.²⁶⁹ Many lack access to well-equipped hospitals and health posts, and clean water. Poverty-related health conditions, such as malnutrition and respiratory disease, further weaken their capacity to cope.

Despite the clear physiological evidence that humidity lowers the temperature threshold for severe human impacts, some epidemiological studies have failed to confirm that relationship. One large review of 23 countries found no clear link between humidity and mortality, and even suggested lower mortality when humidity was high.²⁷⁰ Another study noted the

‘paucity of reported mortality and morbidity impacts associated with observed near Tw 35°C conditions.’²⁷¹ Most recently, researchers²⁷² highlighted the need to reconcile those different findings:

In climate chamber experiments and human energy balance modeling, physiologists find a key role for humidity in driving human heat strain; at high levels of humidity, efficiency of sweating—the main mechanism by which the human body cools itself—decreases. In contrast, epidemiologists conducting time-series analyses comparing health outcomes (i.e., morbidity and mortality) with environmental drivers typically find a negligible role for humidity.

They posited several possible explanations. First, at very high temperatures, humidity may play only a minor role in triggering the main causes of heat-related deaths, such as cardiovascular collapse. Second, many epidemiological studies are geographically limited, often focused on cooler, less humid, high-income regions, and in places where temperature and humidity tend to rise together, which can confound findings. Third, research tends to centre on older, more vulnerable populations whose ability to sweat—and therefore cool themselves—is already impaired, often worsened by dehydration. Fourth, humidity only significantly increases heat stress for inactive individuals at extreme levels of heat and moisture—conditions that are rare in historical records. Fifth, some studies misinterpret how temperature and humidity interact in their models. Finally, daily data may miss short-term weather events like rain that coincide with high heat and humidity, potentially skewing results.

The complexity of heat–health relationships makes such discrepancies unsurprising. In Spring 2022, for instance, dry-bulb temperatures reached 50°C in parts of India, yet only 90 deaths were reported.²⁷³ That was probably at least partially due to poor monitoring and reporting. Resolving those disparities is urgent as the planet continues to warm.

The meteorology of heatwaves

Several climate and weather factors contribute to the onset of dry and moist heatwaves. The predominant factor in dry heatwaves is a strong and slow-moving high-pressure system, which causes air to subside and compress. Sometimes those systems can become ‘locked’ in place by low-pressure zones, prolonging and intensifying the heating.

Large-scale global circulation patterns can reinforce the warming by channelling hot continental air into a region or by blocking cooler air. Dry heatwaves can also be influenced by patterns, such as the El Niño Southern – Oscillation (ENSO), which is a major source of global climate variability that contributes to drought, flooding and extreme heat.²⁷⁴ ENSO can affect heatwave timing and intensity by shifting monsoons, storm tracks and land–ocean temperature contrasts. In India, for example, most years with unusually widespread and intense heatwaves occur one year after an El Niño.²⁷⁵ Land–atmosphere feedbacks can further intensify drought as dry soils limit evaporation cooling.²⁷⁶

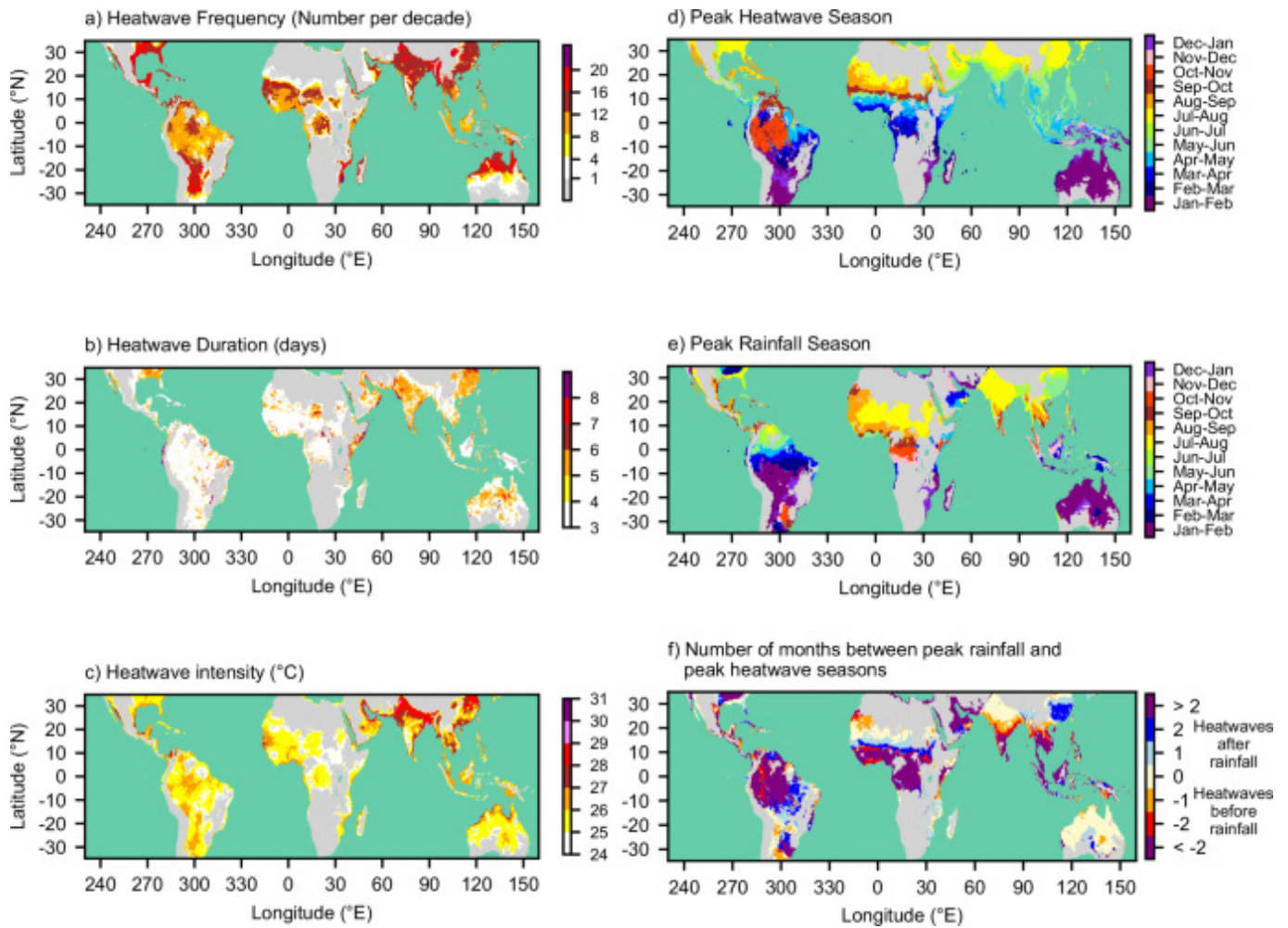
Moist heatwaves develop differently. A recent study of four main global hotspots (the southern Persian Gulf, eastern South Asia, north-central Pakistan and the western Amazon) identified two main drivers: abundant moisture supply and limited atmospheric mixing.²⁷⁷ Winds near the surface push moisture upward, while a layer of warm sinking air aloft prevents storms from forming and removing humidity.

Local factors can further amplify those conditions. Irrigated fields and nearby bodies of water add extra moisture, increasing humid heat.²⁷⁸ As with dry heatwaves, stationary high-pressure systems can amplify moist heatwaves, both by adding heat and by drawing moist warm air from oceans.

ENSO conditions can also contribute by heating the upper atmosphere, producing warmer downdrafts that increase surface heat and humidity.²⁷⁹ In many regions, extreme humid heat has tended to peak during strong El Niño years, such as 1998, 2010 and 2016.²⁸⁰

Unlike dry heatwaves, extreme Tw events tend to occur during the monsoon season. Their link to rainfall often depends on local humidity.²⁸¹ In drier parts of South Asia, Tw extremes coincide with heavier rain, while in more humid regions they tend to occur when rainfall is weak. In semi-arid zones, light rain fuels evaporation and contributes to more frequent and intense extremes (Figure 14).

Figure 14: Humid heatwaves over land in the global tropics and subtropics, and the seasonality of rainfall and humid heatwaves



- a The frequency of heatwaves in each grid cell expressed as the number per decade.
- b The median duration of heatwaves in each grid cell.
- c Heatwave intensity in each grid cell, represented by the 95th percentile of daily mean wet-bulb temperature on heatwave days.
- d The two-month period during a calendar year in which most heatwaves occur.
- e The two-month period during a calendar year in which the highest rainfall occurs in GPM-IMERG (2001 to 2022).
- f The number of months between the month of peak rainfall and the month of peak heatwave occurrence. Regions with no heatwaves are shaded grey.

Source: Lawrence S Jackson et al., 'Daily rainfall variability controls humid heatwaves in the global tropics and subtropics', *Nature Communications*, 2025, 16(3461):3, [online](#).

Humid heatwaves are widespread across the tropics and subtropics (such as in West Africa, India and eastern China to northern Australia, the Amazon, Indonesia, the Philippines and Papua New Guinea), typically occurring once or twice a year. They're shorter and less frequent in drier regions and at higher elevations. Most last from three to six days, and the longest are in in East Africa, India and eastern China.

The highest intensity humid heatwaves (where the daily mean T_w can reach 28°–31°C) occur along the Red Sea and Persian Gulf and in Pakistan, northern India, Bangladesh and northeast China. They tend to peak during monsoon or transitional periods: October–November in the Amazon, March–May near the equator, and July–August in regions such as India, Southeast Asia and West Africa. In some monsoonal areas, including South Asia, they can also appear just before, or early in, the monsoon season.²⁸²

Notes

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