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Exceeding the limits of paediatric heat stress tolerance: the risk of losing a generation to climate inaction

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ABSTRACT

Greenhouse gas (GHG) emissions are creating unprecedented climate-driven extreme weather, with levels of heat and humidity surpassing human physiological tolerance for heat stress. These conditions create a risk of mass casualties, with some populations particularly vulnerable due to physiological, behavioural and socioeconomic conditions (eg, lack of adequate shelter, limited healthcare infrastructure, sparse air conditioning access and electrical grid vulnerabilities). Children, especially young children, are uniquely vulnerable to extreme heat-related morbidity and mortality due to factors including low body mass, high metabolism, suboptimal thermoregulatory mechanisms and behavioural vulnerabilities. Children are also uniquely vulnerable to non-fatal heat-related morbidities, including malnutrition due to agricultural disruptions and cardiometabolic, respiratory and mental illnesses from heat exposure and/or confinement during heat avoidance. Climate mitigation through GHG reductions is central to reducing harms to children and preventing the loss of a generation to climate change. In regions most predisposed to extreme heat-driven mass casualties under various GHG emission scenarios—particularly South Asian and Southwest Asian and North African regions—adaptation tools specific to children's needs are the most urgently needed. Existing public health interventions (eg, cooling infrastructure and preventative educational campaigns) to reduce acute heat mortality, and medical infrastructure capacity to treat heat-related illnesses are currently inadequate to meet children's growing heat resiliency needs. Paediatricians and other clinical and community child healthcare providers in these regions lack education about children's heat risks and adaptation tools. Paediatricians and other child healthcare providers have a crucial role in research, education, clinical practice and advocacy to protect children during extreme heat events. Paediatricians, other child healthcare providers and stakeholders of children's well-being are urged to act on young children's behalf and to elevate youth leadership in GHG mitigation and extreme heat adaptation policy-making.

INTRODUCTION

Anthropogenic climate change is a growing threat to human health and well-being.[1] Extreme heat events (EHEs), or heatwaves, are recognised as one the deadliest consequences of climate change.[2] In this article, we focus on the threat of EHEs in children, who are doubly burdened with heightened vulnerability to extreme heat and the injustice of shouldering a climate crisis that they inherited and did not create. Without conducting a systematic synthesis of prior literature, we reference relevant evidence to provide an overview of key aspects related to this issue. We discuss the unique physiological and developmental attributes of children that heighten EHE health risks; geographies and circumstances that place children at the most immediate risk of EHEs; evidence gaps and a call to action for paediatricians and other child healthcare providers globally.

Human survivability limits to extreme heat

In climate health literature, the term 'survivability limit' refers to physiological conditions that are fatal to a vast majority of humans, while 'adaptability limit' refers to environmental conditions that induce physiological conditions beyond survivability limits. Core body temperatures exceeding 43°C are considered a hard limit to survivability because heat stroke mortality exceeds 99.9%.[3]

Adaptability is strongly influenced by air temperature and humidity. Sherwood and Huber were the first climate scientists to introduce an adaptability limit of 35°C for 6 hours of exposure based on wet bulb temperature, a measure of thermal comfort that incorporates both air temperature and humidity. This adaptability limit is based on evidence that the evaporation of sweat is a critical mechanism of heat dissipation required to keep core body temperatures below survivability limits under hot conditions.[4] Alternative adaptability indices have been proposed, including the wet bulb globe temperature (a weighted average of ambient, wet-bulb and globe temperatures, which incorporates thermal, solar and convective heat transfers from ambient temperature, humidity, solar radiation and wind speed) and the Universal Thermal Climate Index (derived from human energy balance models).[5]

More recent studies suggest that wet bulb temperature adaptability limits are closer to 31°C for healthy adults overall and vary across environments (25°C–28°C in hot-dry environments compared with 30°C–31°C in warm-humid environments) and human developmental stages and activity levels (25.8°C–34.1°C in young adults compared with 21.9°C–33.7°C in older adults in dry-hot conditions).[3 6] These updated studies suggest that the populations expected to be exposed to extreme heat beyond survivability limits are larger than previously estimated.

Important gaps remain in our understanding of heat adaptability limits across vulnerable geographies and human physiologies. For example, there is growing concern that dry and wet-bulb temperature metrics measured in the shade, which are commonly used in public health literature, are not accurate measures of human thermal comfort under real-world EHE exposures. Limited evidence is available regarding how adaptability limits vary across vulnerable populations (eg, children, pregnant women and older adults) when compared with healthy young adults. Critically, limited evidence has identified optimal indices and adaptability limits for infants and children across developmental stages and real-world conditions.

Children's unique vulnerability to extreme heat

Global studies have consistently demonstrated that children, especially young children, are particularly vulnerable to direct and indirect health impacts from extreme heat exposure. Model-based estimates based on extreme heat-related deaths in the USA suggest an OR of 4.4 in infants (children <1 year old) and 1.9 in young children (children 1–4 years old) compared with 1.0 for young adult reference populations.[7] A range of physiological and behavioural factors impact children's metabolic heat production and dry and evaporative heat transfer, contributing to heightened susceptibility to heat stress.

Physical mechanisms of children's vulnerability to extreme heat

Children have innate physiological vulnerabilities to heat stemming from their body composition and metabolic rates. By nature of having smaller body sizes, children have greater body surface area-to-mass ratios than adults, increasing their thermal load when air temperatures exceed their internal body temperature. Under such conditions, a high surface area-to-mass ratio is thought to result in higher environmental heat transfer to children's bodies and lower dry heat losses. In addition, young children have been demonstrated to have higher rates of metabolic heat production per unit mass than healthy adults, often due to biomechanical processes (eg, shorter legs requiring faster strides while running), further increasing their thermal load.[8]

Thermoregulatory mechanisms of children's vulnerability to extreme heat

Children have limited ability to thermoregulate in extreme heat. Human thermoregulation is a homoeostatic feedback control system for maintaining core body temperatures within a narrow range (36.5°C–37.5°C). The most effective mode by which the human body compensates for heat stress is evaporative cooling with sweat production. When a human's core body temperature rises, peripheral vasodilation occurs, which leads to an increased heart rate, stroke volume and cardiac output. This moves warmer blood peripherally to the skin, where it is cooled predominantly by sweat evaporation.

These mechanisms are less efficient in children, especially infants and young children (0–4 years old), and, though evidence is less conclusive, are also believed to be less efficient in older children and adolescents.[9] For example, it has been proposed that children have lower cardiac output and sweat production compared with adults.

Under moderate heat exposures, children maintain adult-like core temperatures even while producing less sweat than adults due to greater sweat evaporative efficiency. However, children's compensation via sweat evaporative capacity does not appear to extend to extreme heat.[8] This is especially true for extreme humid heat, as the high moisture content of the air reduces children's ability to cool with sweat evaporation. This places children at disproportionate risk of overheating in humid heat.

Behavioural mechanisms of children's vulnerability to extreme heat

Children have developmental and behavioural predispositions that render them more vulnerable to extreme heat than healthy adults. Children at various developmental stages have a higher predilection for outdoor play and vigorous activities than healthy adults. This can increase cumulative exposure to heat and, in extreme cases, run the risk of exertional heat stroke—that is, heat stroke brought on by internal heat generated by physical exertion.

In addition, infants and young children have been shown to engage in fewer heat management strategies compared with adults, rendering them dependent on caregivers to guide their adaptative behaviours and remove them from unsafe environmental exposures.[10] Heat stress in all age groups can impair cognition due to the diversion of blood from the brain and other organs toward the skin. Impaired decision-making and caregiving capacity on the part of adults during EHEs can put children at risk of both heat exposure and secondary risks (eg, dehydration, injury and psychological trauma).[11]

Non-fatal effects of heat exposure in children

Children manifest a spectrum of heat-related illnesses, ranging from heat rash (least severe) to heat stroke (most severe and often fatal). Extreme heat exposure has been associated with other acute morbidities in children, including asthma exacerbations, otitis media and externa (ear infections) and bacterial enteritis (infections of the digestive system).[12 13] In utero, extreme heat exposure has also been associated with preterm birth, low birth weight and increased risks of the aforementioned heat-related morbidities over a child's life course.[14 15]

Extreme heat has myriad indirect effects on children's health. Among the largest of these is rising food insecurity. Globally, malnutrition is already one of the leading causes of paediatric morbidity and mortality. More frequent and extreme heatwaves threaten to reverse progress in child nutrition by lowering agricultural crop yields and crop biodiversity and reducing the adaptive capacity of caregivers to access and afford healthy foods.[16] These threats are further compounded by other, sometimes co-occurring, climate-driven extreme weather events associated with food insecurity (eg, drought, cloud burst flooding and storm surge).

Extreme heat has numerous developmental effects on children, including reducing outdoor play, which is essential to children's physical and mental health.[17] Confinement with reduced physical activity contributes to the increasing global prevalence of childhood obesity, which in turn heightens the risk of heat-related illnesses. Childhood obesity also increases the prevalence of adulthood cardiometabolic diseases, which further increase life course heat vulnerability.[18]

The mental health burden of extreme heat is well-documented across age groups but has unique effects on children. Children and adolescents experience higher rates of mental health-related emergency department and hospital admissions compared with young adults during EHEs, especially children with pre-existing mental health conditions. This may in part be due to children's inability to engage in behaviours that are beneficial to their physical and mental health during EHEs, such as outdoor play and socialisation. It may also reflect competing demands on caregivers during EHEs and the unique vulnerability of children to psychological trauma.[19]

Geographies with highest risk of EHE beyond adaptation limits

EHEs exceeding human adaptability have occurred in the South Asian and Southwest Asian and North African (SWANA) regions, resulting in mass causalities. In Bangladesh, tens of thousands of heat-related deaths occur annually and have been increasing by approximately 20% per year for the past decade.[20] In Makkah, Saudi Arabia, an area where air temperatures can exceed 51°C and wet-bulb temperatures have been steadily increasing, over 1300 people died in June 2024 due to extreme heat exposure during the Hajj pilgrimage.[21]

In the future, the SWANA region and parts of South Asia are projected to experience the largest increase in heat-related death rates by the end of the century. For example, a recent study demonstrated that Saudi Arabia is projected to experience a 13-fold increase in heat-related deaths even in low-greenhouse gas (GHG)-emission scenarios (2°C global warming scenario), and up to a 63-fold increase in heat-related deaths under high-GHG-emission scenarios over 2061–2080.[22] In South Asia, projections of heat-related mortality are more challenging to estimate across GHG emission scenarios due to the paucity of heat mortality data in many countries in this region.[23] However, large populations lacking access to air conditioning, heat shelters, or acute care for heat-related illnesses suggest that heat-related mortality could reach unprecedented, existential proportions in some regions.

Evidence gaps on children's vulnerability to extreme heat in the SWANA and South Asia regions

Currently, South Asia has the highest percentage of children (76%, 460 million) exposed to extreme heat than any other global region. The WHO estimates that annual child mortality rates due to extreme heat exposure will surpass 100 000 deaths per year by 2050 globally, with the greatest child mortality rates occurring in South Asia.[24]

However, most of the evidence detailing children's vulnerability to extreme heat exposure is based on populations in regions of the world outside of South Asia and the SWANA region.[25 26] This calls into question the transportability of existing evidence and the resulting accuracy of current child EHE mortality forecasts. Research is needed to evaluate child heat mortality associations in the world's most at-risk regions to ensure that future model projections and adaptation efforts accurately focus on populations most vulnerable to health harms from EHEs.

The primacy of mitigation

No approach to climate resiliency is sustainable without reducing atmospheric GHG emissions. Children bear a triple burden of climate change due to their vulnerability to extreme heat, lack of independent resources and dependence on adults for basic needs, and injustice due to inheriting a climate crisis they did not create. Despite this disproportionate burden, youth climate leaders are rarely included in international and local policy initiatives that aim to achieve emission goals in line with the 2015 Paris Agreement. Multisector climate action must engage youth perspectives through initiatives such as the International Youth Climate Delegate Programme, the first-ever youth-led programme within the UN Climate Change Conference that debuted at the 2023 COP 28 meeting.

Gaps to achieving adaptation targets

In parallel with mitigation efforts, initiatives that increase the adaptive capacity of communities are needed to protect children. Particular emphasis is needed for the SWANA and South Asia regions, which already experience extreme heat and will be predisposed to mass casualties under the range of GHG emission scenarios. As part of the Paris Agreement's Global Goal on Adaptation framework, the UAE Framework for Global Climate Resilience was introduced at COP 28. This framework highlighted financial, political and logistical challenges faced by countries in this region in achieving adaptation targets related to (1) impact, vulnerability and risk assessment, (2) planning, (3) implementation and (4) monitoring, evaluation and learning.[27] In this section, we review child health-relevant adaptation challenges and opportunities to improve children's resiliency to extreme heat, with an emphasis on the highest-risk geographies of SWANA and South Asia.

Education

There is limited evidence assessing climate knowledge among those responsible for children's health and well-being in SWANA and South Asia (eg, public health officials, school administrators, paediatricians and other child healthcare providers). Preliminary studies among physicians in South Asia identify a lack of climate knowledge as a primary barrier to educating patients about their extreme heat-related health risks and actions they can take to improve their climate resilience.[28]

Studies have shown wide variability in the implementation of climate change education in adaptation policies across South Asia.[29] Unequal knowledge exacerbates children's vulnerabilities and disparities, given their dependence on caregivers to guide behaviour and maximise survival during EHEs.

Healthcare system

Healthcare systems in the South Asia and SWANA regions are experiencing increasing demand for acute care due to extreme heat exposure. In Karachi, Pakistan, frequent heatwaves during the 2024 summer season, with air temperatures surpassing 52°C, resulted in thousands of people experiencing heatstroke, straining ambulance and emergency room services.[30] In India, the world's first dedicated heat stroke emergency room opened in Delhi in 2024 due to a surge in life-threatening heat illnesses. Though most heat stroke cases documented in these EHEs occurred among older adults and adults with occupational exposures, rates of heat stroke in children are expected to follow as global temperatures continue to rise.[31]

Examples of needed initiatives include system-level EHE disaster preparedness with embedded programmes specific to children's heat health; data-informed approaches to monitoring and real-time response during EHEs; and scalable emergency medical services to ensure that children experiencing heat stroke are connected to hospital care rapidly enough to prevent death and severe morbidity.[32,33]

Limits of existing adaptation approaches

Infrastructural drivers of extreme heat vulnerability vary across nations in the SWANA and South Asia regions. In Delhi, India, higher rates of population-level heat stress have been demonstrated in low-income to middle-income neighbourhoods, which are more likely to have dense settlement patterns, poor housing quality and an absence of cooling solutions such as air conditioning and vegetation.[34] Even in more affluent areas able to afford air conditioning, electrical grid vulnerabilities place these communities, in essence, one power blackout or brownout away from a life-threatening EHE.

Urban vegetation, which reduces heat islands through shade and evaporative cooling, is effective in reducing high temperatures in various high-income global regions.[35] However, in low-income and middle-income regions of SWANA and South Asia, establishing this sort of green infrastructure has been hampered by implementation and maintenance barriers, including prohibitive irrigation requirements in arid climates.[36] Moreover, when EHEs are accompanied by very high relative humidity—conditions that are particularly dangerous due to diminished evaporative cooling of sweat—vegetative cooling is also less effective due to inhibited evaporation of water.[37]

As highlighted in the Paris Agreement's Global Stocktake, when adaptation is informed and driven by local contexts, populations and priorities, both the adequacy and effectiveness of adaptation action and support are enhanced, which can promote transformational adaptation.[38] This emphasises the need for financial and political support for bottom-up approaches to adaptation solutions that centre the heat health risks of vulnerable populations in the context of their lived environments.

Emerging technologies

If global mitigation goals are not achieved, existing cooling technologies risk failure under extreme warming projected by the end of the century, particularly in the hottest geographies including SWANA and South Asia. More frequent power grid failures due to EHEs reduce the utility of cooling technologies that depend on stable electricity (eg, affordable air conditioning units). High albedo surfaces (eg, cool roofs and super cool roofs) that reflect solar energy into the atmosphere have been shown to reduce the urban heat island effect by up to 3°C and reduce localised air temperature by just over 1°C, which may not be enough of an effect to protect vulnerable populations during EHEs that far exceed adaptability limits.[39,40] As latent warming is expected even with low-GHG-emission scenarios, there is a need for novel cooling technologies to protect large populations in heat-vulnerable regions of the world. These efforts must be a complement to, and not a detraction from, ongoing mitigation and adaptation efforts.

Role of paediatricians and other child healthcare providers: a call to action

Research consistently shows that physicians are one of the most trusted voices for instilling resilient behaviours in climate-vulnerable populations and are important advocates for systemic change to support children's well-being, including in climate justice advocacy.[41] In the context of EHEs, roles for paediatricians and other child healthcare providers include:

1. Advocate for the incorporation of climate and planetary health education across undergraduate, graduate and continuing medical education.
2. Leverage healthcare training to disseminate basic information about child heat stress vulnerabilities to child caretakers beyond traditional healthcare and public health sectors.
3. Participate in clinical trials to explore novel preventative and therapeutic interventions for heat stroke in children that are scalable to the most heat-vulnerable regions of the globe.
4. Codevelop and pilot community-centred, healthcare system emergency management response workflows specific to EHEs.
5. Advocate for global GHG mitigation policies by emphasising the health impacts of global warming on children while also contributing to local mitigation efforts, including reductions in the healthcare system's contribution to GHG emissions.
6. Partner with climate justice organisations to advocate for increased climate adaptation funding and the just distribution of existing adaptation resources to children in communities most vulnerable to extreme heat.
7. Amplify local youth voices and leadership in mitigation and adaptation initiatives broadly.

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