Heat and Health 2

Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities

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Heat extremes (ie, heatwaves) already have a serious impact on human health, with ageing, poverty, and chronic illnesses as aggravating factors. As the global community seeks to contend with even hotter weather in the future as a consequence of global climate change, there is a pressing need to better understand the most effective prevention and response measures that can be implemented, particularly in low-resource settings. In this Series paper, we describe how a future reliance on air conditioning is unsustainable and further marginalises the communities most vulnerable to the heat. We then show that a more holistic understanding of the thermal environment at the landscape and urban, building, and individual scales supports the identification of numerous sustainable opportunities to keep people cooler. We summarise the benefits (eg, effectiveness) and limitations of each identified cooling strategy, and recommend optimal interventions for settings such as aged care homes, slums, workplaces, mass gatherings, refugee camps, and playing sport. The integration of this information into well communicated heat action plans with robust surveillance and monitoring is essential for reducing the adverse health consequences of current and future extreme heat.

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This is the second in a Series of two papers on heat and health

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Introduction

The first paper in this Series outlined the negative health effects of human heat stress, and the greater health risk associated with the increased exposure to extreme heat and hot weather projected with climate change.[1] In many countries, extended bouts of very hot weather (ie, heatwaves) are already responsible for more deaths than all other natural disasters combined,[2] with people 65 years and older, especially those with comorbidities such as cardiovascular disease, among the most vulnerable.[3] Coping with heat extremes is particularly challenging for people with lower socio-economic status who cannot afford air conditioning or or have restricted access to clean drinking water.[4] The negative effects of hot weather are also far-reaching and can include impacts on occupational health and productivity[5] and population health effects related to the ability to remain physically active and play sport safely.[6] Urbanisation, features of the built environment, and other factors associated with population growth often heighten exposures to extreme heat that endanger health. Heat extremes are already lasting longer and growing in frequency and intensity; extremely hot weather currently considered rare will be increasingly commonplace.[7] Efforts to reduce carbon emissions (climate change mitigation) and alter the long-term warming trajectory of the planet are ongoing.[8] However, given the inevitable rises in global and local temperatures over the coming decades, identifying effective prevention and response measures that can be implemented, particularly in low-resource settings, has never been more important.[9] This Series paper describes how the risks of human hyperthermia and other heat-related health problems described in the first paper in this Series[1] can be reduced by introducing accessible and sustainable interventions at the landscape and urban, building, and individual scales. We also describe the barriers and opportunities for the implementation of these solutions in settings such as aged care homes, slums, workplaces, schools, mass gatherings, refugee camps, and sport. We conclude by detailing key components of heat action plans and considerations for their effective implementation to

Key messages

- Evidence-based cooling strategies during heat extremes and hot weather are urgently needed to cope with the health risks associated with the inevitable trajectory of climate change
- Air conditioning is set to become the most widely adopted heat reduction strategy worldwide, yet it is unaffordable for many of the most vulnerable, financially and environmentally costly, and leaves many defenceless from extreme heat during power outages
- Strategies at the landscape and urban (eg, blue and green spaces) and building (eg, changing materials and natural ventilation) levels can greatly augment society's adaptive capacity to heat extremes and hot weather
- Effective cooling solutions can be adopted at the individual level, even in low-resource settings, which are more sustainable than air conditioning, and focus on cooling the person to relieve physiological heat strain, as opposed to cooling the surrounding environment
- Heat action plans that are robust, evidence-based, well communicated, and informed by real-time surveillance provide optimal health protection

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***Panel 1:* Benefits and negative effects of the use of air conditioning for cooling**

Benefits

- Exceptionally protective against adverse health effects of extreme heat
- Reduces subjective thermal discomfort, particularly at the upper edge (approximately 30°C) of the comfort zone
- Improves indoor workplace productivity, particularly in tropical and subtropical climate zones where population growth, economic development, and urbanisation are focused

Negative effects

- Drives a burgeoning demand for electricity, which is predominantly generated by fossil fuels and thus increases global greenhouse gas emissions
- Energy requirements of mass cooling during bouts of extremely hot weather can exceed supply capacity leading to unplanned power outages
- Contributes to the urban heat island effect, particularly in the most densely populated megacities, reinforcing demand for cooling
- Not viable in outdoor and semi-outdoor environments
- Capital and operational costs exclude many of the most vulnerable sections of the community from acquiring the benefits
- Removes stimulus for physiological and perceptual adaptation to the heat

adapt to, and thus cope with, current and future extreme heat. The included scientific literature was identified following a targeted review based on the expertise of the authors, focused to illustrate key issues within each domain considered.

Air conditioning: a widespread but unsustainable cooling solution

Cooling the indoor microclimate with vapour-compression refrigeration cycle air conditioning technology, is set to become the most prevalent strategy worldwide for coping with hot weather and heat extremes.[10] Worldwide air conditioning sales have climbed steeply during the past few decades. The International Energy Agency estimated that annual sales nearly quadrupled to 135 million units between 1990 and 2016.[11] Approximately 1·6 billion air conditioning units are now in use globally, half of which are in China and the USA. Cooling indoor spaces with air conditioning is the fastest growing use of energy in buildings, particularly in the hot, humid tropics and adjacent subtropical regions where global economic growth is concentrated, but also in industrially advanced economies at higher latitudes where consumer comfort expectations continue to rise.

From a health perspective, use of air conditioning provides numerous benefits (panel 1). Reductions in indoor temperatures dramatically alleviate heat strain. A working air conditioning unit in a home is the strongest protective factor against heat-related fatalities.[12] In hospital wards, its presence reduces the risk of mortality during a heat extreme by 40%.[13] Air conditioning use in workplaces improves productivity and reduces labour costs,[14] and in learning environments improves classroom performance.[15] In general, the strongest driver for air conditioning adoption is improved thermal comfort. Traditionally, optimum indoor comfort temperatures were widely accepted to be 22–25°C,[16,17] regardless of the building's climatic context or the occupants' cultural background. Since 2004, the adaptive thermal comfort model[18] that defines the indoor comfort temperature on the basis of exposure of occupants to outdoor temperatures, expanded this range to 21–29°C.[18,19]

Widespread air conditioning use, however, also has far-reaching negative effects (panel 1). Energy use for space cooling with air conditioning in residential and commercial building sectors can exert extreme pressure on electricity grids during peak-demand episodes that coincide with heat extremes. For example, space cooling contributed three-quarters of Philadelphia's (PA, USA) peak electricity demand during a heat extreme in July, 2011,[20] whereas in Beijing (China), air conditioning accounted for more than half of the peak load during a heat extreme in July, 2017.[11] If peak demand exceeds the maximum supply provided by the grid, unplanned blackouts, or deliberate load shedding (or brownouts) occur, often leaving many people without power during the hotter parts of a day. Such power disruptions contributed to surges in heat-related mortality in Pakistan in 2015 and 2018, and in Australia, due to the prevalence of household air conditioning, are conservatively estimated to increase the risk of dying in extreme heat due to heat-related illness by 50%.[21] Also, mortality due to accidents including heat stroke increased by 122% during the 2003 power outage in New York City (NY, USA).[22] Although the acceleration in air conditioning usage worldwide will further exacerbate these challenges, it will also present a vicious cycle: a warmer climate leads to greater reliance on and use of air conditioning, which in turn contributes to further warming, depending on the source of electricity generation. On a local scale, air conditioning units produce anthropogenic waste heat.[23] On a global scale, direct refrigerant emissions of air conditioning units are powerful greenhouse gases, although their climatic impacts are minor compared with the emissions related to the electricity generation required to support its use. From 1990 to 2016, the contribution of air conditioning to total energy-related CO_2 emissions attributed to buildings, mainly caused by fossil-fuelled power stations, more than doubled.[11] Space cooling contributed about 1 billion tonnes of CO_2 emissions to the planet's atmosphere in 2019,[24] about 3% of the total global energy-related CO_2 emissions (approximately 33 billion tonnes).[25]

Access to air conditioning is severely scarce among many of the most vulnerable to the health impacts from heat. Despite decreasing capital costs since about 2000, air conditioning remains financially inaccessible to certain populations due to the costs of electricity and maintenance, or substandard housing.[26] Urban–rural disparities in access to air conditioning are exemplified in China, where urban residents had 142·2 air conditioning units per 100 households in 2018, compared with 65·2 units per 100 rural households.[27] People older than 65 years, who are at a much greater risk than younger adults (18–40 years) of heat-related illness during extreme heat exposure,[1] are more likely to be both confined indoors and have experienced fuel poverty.[28] By contrast, for people who have air conditioning, the habitual cooling of buildings and vehicles in periods of hot weather reduces the opportunities for physiological and behavioural adaptation (ie, heat acclimatisation).

Identifying and implementing sustainable cooling strategies that are broadly accessible to all sections of society is a pressing need to support adaptation to a warmer future, especially for those who are most economically and clinically vulnerable to heat extremes. To establish optimal solutions, a more holistic understanding is required of the factors that contribute to the severity of heat stress at the individual level, and ultimately the risk to human health and wellbeing during hot weather and heat extremes.

The heat cascade

Heat stress at the individual scale results from a series of interacting systems that generate a top-down heat cascade whereby the excess heat load at the landscape and urban level is transferred to the building level, and then to the individual (figure 1). Higher ambient temperatures resulting from global climate change will be further intensified by rapid urban development that prioritises high density housing surrounded by minimal vegetation and constructed from low-cost materials with poor thermal properties. Collectively, these factors have the potential to progressively worsen the heat stress a person must physiologically manage both indoors and outdoors during hot weather. Features of the indoor and outdoor thermal environment can be altered to reduce the amount of heat that is transferred from one level of the heat cascade to the next.

Fundamental principles of heat transfer

At all levels of the heat cascade, the fundamental principles that govern patterns of heat exchange remain constant. Convective heat transfer from a hotter surface to a cooler environment (eg, skin to air) is accelerated with increasing air speeds. The evaporation of moisture from a surface, such as sweat from the skin, or water from leaves, is also enhanced with increasing air speeds but attenuated by high ambient humidity. Radiant heat sources (eg, sun) contribute thermal energy to a system in the form of electromagnetic waves and can be modified by the surface absorptivity and reflectivity of objects such as buildings and trees. Heat is transferred from a hotter to cooler environment through solid materials such as roofs, walls, and floors by conduction at a rate that is altered by the insulative properties and thickness of the conducting solid.

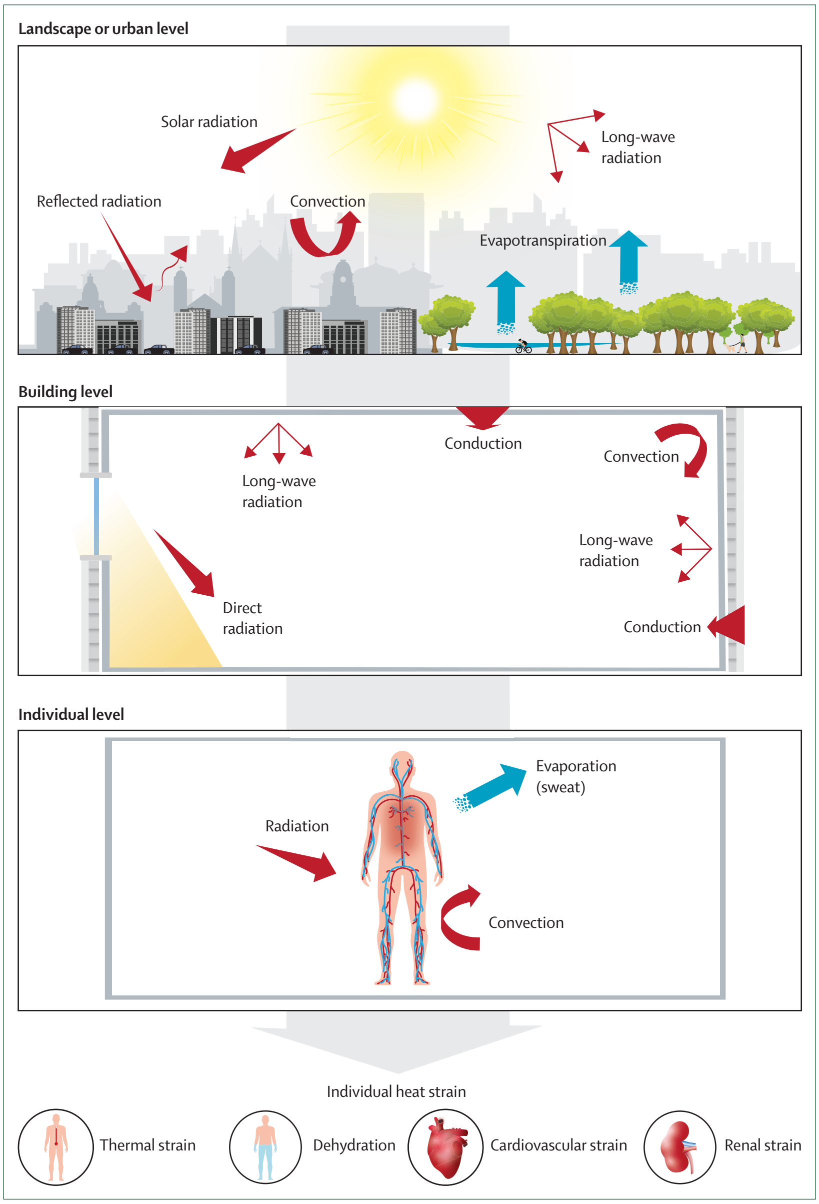


Figure 1: **Heat transfer pathways at all levels of the heat cascade**
Pathways that form the heat cascade from the landscape and urban level, to the building level, and then to the individual level, result in physiological heat strain, which is ultimately responsible for a large proportion of heat-related morbidity and mortality.

	Benefits	Limitations
Landscape and urban scale		
Water bodies	If lakes with high heat capacity stay cooler than air, they cool the air via convection and evaporation. Evaporative and convective cooling effects are more pronounced with increased wind across large lake surfaces (ie, lake breezes). Fountains providing spray with moving water accelerate evaporative cooling. Bodies of water provide cooling options at the individual level (eg, dousing and immersion).	Lakes require large areas of open space. Can increase local humidity if air is stagnant and water mixing is low. Cooling effect diminishes as water warms (eg, throughout summer). If accessible for individual level cooling strategies, water should meet appropriate sanitation standards. Increased risk of drowning.
Grass and plants	Large grasslands with trees and other shading (eg, parks), vegetation on rooftops, and green building facades provide cooling via evapotranspiration from leaves and evaporation from soil. Vegetated surfaces also reduce surface temperatures on the ground and walls, and reduce the infrared (longwave) radiation. Help manage stormwater.	Parks require large areas of open space and can increase humidity and discomfort if wind flow is insufficient or there is no shading. High maintenance requirement of vegetation on buildings. Building vegetation debris at street level. High water use, with requirement dependent on climate zone (eg, temperate *vs* desert region).
Shading infrastructure	Artificial canopies strategically located over outdoor areas (eg, transit stops, play areas, and picnic areas) and buildings minimise radiative heat load while maintaining convective flow across surfaces underneath. Building shade can be strategically used to provide shading for pedestrians and high-use urban areas (eg, plazas and transit stops).	High cost of canopy materials. Coverage dependent on size, height, and orientation of shading. Shading implementation should assess use (eg, time of day and demographics) to ensure shade is optimally cast at the hottest times of day.
Trees	Provide radiative shading and evapotranspiration. Low penetration of shortwave radiation reduces temperature in shade at ground level. Provide essential ecosystem services often absent in urban areas. Help manage stormwater.	Evapotranspiration dependent on tree type. Can reduce vertical air mixing inside street canopies leading to slower dilution of pollution than normal. Can increase overnight air and surface temperatures by blocking outgoing infrared radiation. Expensive to implement and maintain.
Urban ventilation pathways	Higher natural air flow around buildings and along streets increases convective heat losses from surfaces. Especially effective when combined with blue and green infrastructure.	Difficult and costly to implement after buildings and urban plan have been established. Cooling effectiveness dependent on prevailing wind direction and speed, specifically during the hot months of the year, and air and surface temperature gradients.
Traffic infrastructure	Reducing road and vehicle density mitigates greenhouse gas and heat emissions from vehicles. Reduced concentration of heat retention characteristics of road surfaces reduces heat absorption and retention.	Reduces urban accessibility and mobility without parallel improvements in public and active transport infrastructure.
Active transport infrastructure	Lower operating cost per passenger per km of cycling and walking than cars, buses, or trains. Secondary health benefits for disease prevention and management. Reduces travel time. Reduces vehicle collision injury risk.	Without parallel alterations in traffic infrastructure, increases exposure potential to pollution. Increases risk of exertional heat stress.
Electric vehicle fleets	Lower heat and CO_2 emissions than conventional vehicles for the same mileage.	High capital costs. Requires extensive charging infrastructure and natural resources (eg, minerals) for production of rechargeable batteries.
Building scale		
Coatings	Highly reflective coatings on roofs, external walls, and streets work by reflecting incoming solar radiation, thereby reducing heat gains by buildings and the urban fabric. Super-cool coatings enhance the longwave radiative heat losses from roofs, external walls, and streets by focusing their radiative emissions within the very specific wavelengths known as the atmospheric window.	Wall coatings in densely built environments might lead to reflected solar radiation being absorbed by adjacent buildings or street-level pedestrians. Reflective coatings can be expensive.
Insulation	Increasing insulation of roofs and walls reduces net conductive heat flow from the outdoor to indoor environment. Insulative materials can be retrofitted to existing buildings and included in new buildings.	Higher labour and material costs. Not all buildings are amenable to insulation retrofits (eg, some flat-roof construction types).
Glazing	High-performance glazing systems and films minimise solar heat gains and maximise infrared radiative losses back to the external environment.	Retrofitting glazing is costly, potentially impacts architectural heritage, and sacrifices a large amount of embodied energy in the existing fenestrations.
Window shading	External awnings can block direct solar radiation entering the indoor environment specifically through windows. Double-skin facades reduce net heat gain through walls and windows.	External awnings, blinds, shutters, and other window coverings can block natural ventilation. Double-skin facades are costly and not retrofittable.
Natural cross ventilation	Paired inlets and outlets in the building facade strategically oriented in relation to the winds prevailing during the hottest months of the year can increase convective losses from building thermal mass, and enhance convective and evaporative heat losses directly from the building occupants.	For existing buildings, effectiveness is dependent on orientation and window locations. Not easily retrofitted to extant building stock. External noise through windows.

(Table continues on next page)

	Benefits	Limitations
(Continued from previous page)		
Individual scale		
Electric fans	Can accelerate convective and evaporative heat losses from the skin resulting in reduced physiological heat strain and improved thermal comfort. Up to 50 times lower electricity requirement than air conditioning. Simple devices that are more affordable and accessible to many heat-vulnerable people. Switching from air conditioning to fans can reduce peak electricity demand and associated risk of power outages during hot weather. Require electricity, but battery or solar-powered options available.	Accelerates body heating and worsens physiological heat strain when used at >45°C, most prominently with low humidity. Cooling effects of fans diminish with age and other conditions that reduce sweating unless used in conjunction with skin wetting. Newly proposed simplified temperature thresholds for safe fan use, irrespective of humidity, are 39°C for healthy adults aged 18–40 years, 38°C for healthy adults aged >65 years, and 37°C for those older adults taking anticholinergic medications. High rates of water ingestion needed to offset accelerated dehydration, which can be particularly challenging when fans are used during sleep overnight.
Self-dousing	Applying water to the skin (eg, with a spray bottle or sponge) or donning wet clothing increases evaporative heat loss without additional sweating. Reduces physiological heat strain and thermal discomfort. Effective up to at least 47°C. Water unsuitable for drinking can potentially be used for sponge dousing. Can be used during power outages if water supply available.	Not effective if protective equipment or other clothing requirements restricts evaporation of water directly from the skin. Dousing should be repeated regularly (eg, about every 5–10 min) to ensure skin remains wet. Sustained supply of water required.
Foot immersion	Immersing feet to above the ankles in cold water promotes conductive heat loss. Reduces sweating and improves thermal comfort. Suitable for use during power outages if water supply available.	Has not been shown to reduce physiological heat strain. Very cold water (<5°C) can induce intense local thermal discomfort. Increased risk of slips and falls.
Misting fans	Electric fans that emit high-pressure water spray can enhance evaporative heat loss from the skin without additional sweating. Reduces physiological heat strain and thermal discomfort. Can reduce air temperature immediately around a person by extracting latent heat energy from the air, especially in arid climates, and from hot surrounding surfaces.	Not suitable for most indoor applications, unless spray volume is reduced. If area of use is not well ventilated, increases in humidity reduce cooling effectiveness. Increased risk of slips and falls. Clean water and electricity supply required. Restricted cooling range (within about 2–3 m).
Evaporative coolers	Forcing air across a wet membrane reduces air temperature by extracting latent energy. Air temperature reductions of up to 10–15°C possible in arid climates.	Minimal cooling effect in humid climates. High capital costs. Without maintenance can become mosquito breeding sites.
Ice towels	Crushed ice wrapped in a damp towel applied to the neck and chest increases heat loss via conduction. Damp chilled towels temporarily draped over the head and lap also augment evaporative heat loss. Short (1–2 min), repeated (about every 10 min) application can reduce physiological heat strain and thermal discomfort.	Preparation is labour and time intensive. Depending on conditions, can melt and become ineffective within approximately 30 min. Ice supply required. Low portability.
Cold water ingestion	Provides internal conductive heat transfer between hot body and cool ingested fluid. Can prolong exercise in hot and humid climates.	Internal cooling effect can be offset by parallel reductions in sweating. If ingested after sweating starts, negligible effect on core temperature. Drinking very cold water might decrease the amount of fluids ingested.
Reducing activity	Breaks in physical activity >5–10 min reduces metabolic heat production sufficiently to lower body temperature.	Breaks must be compatible with productivity goals in occupational settings. Benefits limited if other cooling behaviours are not permitted (eg, shade and removing clothing).
Optimising or removing clothing	Removing or modifying clothing or protective equipment reduces resistance to sweat evaporation and convective heat exchange at skin surface. Strategically placed vents can assist sweat evaporation.	Can compromise safety if clothing or equipment serve protective function. Clothing ensemble should be easily modifiable. Can compromise skin protection from ultraviolet radiation.

Table: **Benefits and limitations of sustainable cooling strategies during heatwaves and hot weather at the landscape and urban, building, and individual scales**

Sustainable cooling strategies at the landscape and urban, building, and individual levels of the heat cascade

Sustainable interventions at the landscape and urban, building, and individual levels (table) can be applied to alter patterns of heat transfer, disrupt the heat cascade, and ultimately minimise the accumulation of heat inside the human body during heat extremes and hot weather.

Landscape and urban level

The outdoor thermal microclimate is predominantly established by prevailing weather conditions, but is also influenced by features of the urban environment and surrounding landscape that modify localised heat retention. So-called blue infrastructure (ie, bodies of water) exerts a moderating influence over the urban microclimate, mainly due to a high heat capacity. The evaporative cooling benefits are more pronounced with higher wind speeds, drier air, and if water is in motion (providing some spray) as opposed to stagnant.[29] So-called green infrastructure, such as vegetation at street level, on rooftops, or on building facades, moderates urban microclimates through transpiration from leaves, evaporation from soil moisture, and casting shade. Parks with elevated shading canopies are more effective urban climate moderators than unshaded grass-covered terrain.[30] Larger parks with adequate tree canopies are capable of forming so-called urban cool islands that supply thermal relief to adjacent residential and commercial precincts.[30,31]

The use of cool roofs (see building level section) also reduces urban temperatures to minimise surface temperatures and heat retention in the urban fabric.[32,33] A 2018 study[34] projected that simultaneous high-intensity implementation of cool roofs and street trees across the USA would decrease projected daytime mean and extreme air temperatures by the end of the century; however, overall night-time warming by 2–7 K is expected, dependent on the region and emissions scenarios. Many of these measures, however, come with trade-offs in terms of cost for implementation, maintenance, and water use,[35] which should be evaluated before and throughout a green infrastructure project.

Urban designers are strategically applying novel shade types in cities, such as the use of advanced kinetic photovoltaic panels that can ameliorate street-level microclimates and minimise solar heat gain by buildings, all while converting solar radiation into electricity. For example, Abu Dhabi's Al Bahr Towers (United Arab Emirates) have more than 1000 moving hexagonal shades across each tower's facade, providing shade in the daytime and closing overnight to allow emitted heat to escape the city.

By combining passive shading strategies with green and blue infrastructure, and purposive urban ventilation pathways,[36] the worst effects of urban overheating can be tempered. Moderating overall amounts of urban heat as opposed to only focusing on the rural-to-urban temperature differences (ie, urban heat island)[1] should dampen demand for air conditioning, thereby reducing waste heat, thermal pollution, and the release of greenhouse gases caused by mechanical conditioning. Cooling cities by ridding them of waste heat necessitates greater planning to manage anthropogenic heat from vehicles and transportation, buildings, air conditioning, and industry in densifying cities,[1] enhanced heat recovery and recycling (such as water heating) and continued improvement in the coefficient of performance for mechanical conditioning equipment. Peak traffic volumes in one North American city raised the temperature of near-highway air masses by 1·3°C on average compared with temperatures at weekends.[37] Transitioning to electric vehicle fleets and improving public transportation are already viable heat-reduction strategies, which can be further aided by improving cycling infrastructure, urban walkability, and access to low-power methods of active transport, including e-scooters, mopeds, and e-bikes.

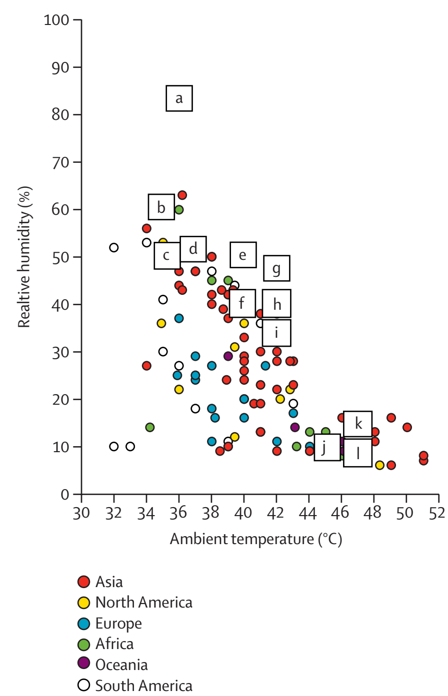
Building level

Heat enters the indoor environment via conduction through walls, roofs, and floors, and by direct radiation through windows. The temperature of external building surfaces is a consequence of its material properties (eg, conductivity and heat capacity), colour, net radiant heat load, and any convective and evaporative heat losses. Natural cross ventilation through building openings also enables convective heat transfer between the inside and outside of a building. Retrofitting roofing of buildings with novel coatings that are highly reflective in the solar wavelengths 0·3–2·5 μm can considerably reduce the cooling load on buildings (cool roof). Advances since 2015 in so-called super cool roof polymer materials have combined the high solar reflectivity of cool roof materials with near-perfect thermal radiation emission through the atmosphere's infrared longwave window (8–13 μm) to the cold, outer space. The combined shortwave and longwave properties of super cool polymer coatings enables net radiative losses from roofing as high as approximately 96 W/m².[38] The resultant passive daytime radiative cooling effect can be as much as –9 K,[38,39] presenting strong potential for reductions in the electricity demands of indoor air conditioning.[40] Rooftop sprinklers enhance evaporation and reduce the net heat load on a building, whereas vegetated surfaces (eg, so-called green walls) can also reduce surface temperatures and attenuate the infrared (longwave) radiation penetrating a building. At street level, reflective pavements and wall coatings are less effective due to the reflected solar radiation being absorbed by adjacent buildings and pedestrians.[41–43] At these low levels within the urban canopy, strategic orientation of buildings and trees for maximum shading accounting for summer daytime solar angles (eg, shading south side in northern hemisphere summer) can enhance pedestrian comfort and reduce energy demands. However, consideration of wind flow for evaporative and convective cooling outdoors (and indoors for naturally ventilated buildings) is needed[44] through the use of prevailing seasonal winds (ie, wind roses).[45] These changes can also help minimise indoor overheating and the need for active cooling, particularly when paired with adequate insulation and daytime indoor shading strategies (curtains, shade, and shutters on south and southwest facing windows).

Individual level

During heat extremes and hot weather, cooling strategies that are low cost, accessible, and sustainable can be implemented at the individual level to drastically reduce physiological heat strain characterised by rises in core temperature (thermal strain), cardiovascular strain, and dehydration, and subsequently reduce the risk of heatwave hospitalisation and death.[1] Forcing air across the skin with devices such as electric fans has a 10–50-times lower electricity requirement and cost than cooling surrounding air with air conditioning. Even without any accompanying chilling, fans accelerate convective heat loss provided there is a positive skin-to-air temperature difference. When air temperatures exceed that of fully vasodilated skin (35°C), dry heat begins to flow into the body instead of out the body,[46] which is probably why many public health agencies (eg, WHO, the UK National Health Service, and the US Centers for Disease Control and Prevention) advise against fan use when temperatures rise above this threshold. However, fans can still be very effective in accelerating evaporative heat loss, especially in humid conditions.[46] Laboratory studies show that fans attenuate heat-related elevations in cardiovascular and thermal strain in resting young (23 years; SD 3), healthy adults at air temperatures up to 42°C with 50% relative humidity.[47] The cooling benefits of fans in very humid conditions (42°C, 50–70% relative humidity) are eliminated in older adults (>65 years) due to reduced sweating with age.[48,49] Such high temperature and humidity combinations have not been reported in any major global heat extreme event between 2007 and 2019 (figure 2), but the translation of outdoor (landscape and urban level) conditions to the indoor environment is heavily dependent on characteristics at the building level of the heat cascade.[58] Very high air temperatures (>45°C) are usually accompanied by lower humidity (figure 2). Because most sweat readily evaporates without supplemental airflow in these conditions, fan use worsens physiological heat strain[47] and should not be recommended. The US Environmental Protection Agency[59,60] warns against fan use above a critical heat index, a unified metric combining temperature and humidity. However, fans are detrimental in very hot, dry conditions that yield a lower heat index than the hot, humid conditions under which fans are beneficial.[47] A 2021 biophysical modeling study, supported by these physiological data, proposes new simplified temperature thresholds for safe fan use that can be directly used in public health heatwave policy documents.[61] These are 39°C for younger, healthy adults

	Participants, activity*	Thermal strain	Cardiovascular strain	Dehydration
(a) Electric fans[46]	Young adults, rest	√	√	x
(b) Electric fans[50]	Young and older adults, intermittent exercise	√	√	x
(c) Ice ingestion[51]	Young adults, continuous exercise	=	=	√
Misting fan[52]	Young adults, intermittent exercise	√	√	√
(d) Ice towels[53]	Young and older adults, intermittent exercise	√	√	
Electric fan and self-dousing	Young and older adults, intermittent exercise	√	√	
(e) Electric fans[47]	Young adults, rest	√	√	x
Self-dousing[54]	Young adults, rest	=	√	√
Foot immersion	Young adults, rest	=	=	√
(f) Hand and forearm[55] immersion	Young adults, intermittent exercise	√	=	√
(g) Electric fans[46]	Young adults, rest	√	√	x
(h) Electric fans[48]	Older adults, rest	=	=	x
(i) Wet shirt[56]	Older adults, rest	√	√	√
Electric fan and wet shirt		=	=	=
(j) Electric fans[57]	Young adults, intermittent exercise	=	=	=
Electric fan and self-dousing	Young and older adults, intermittent exercise	√	=	=
Ice towels	Young and older adults, intermittent exercise	√	=	=
(k) Electric fans[47]	Young adults, rest	x	x	x
(l) Self-dousing[54]	Young adults, rest	=	√	√
Foot immersion	Young adults, rest	=	=	√



√ beneficial
= no difference
x detrimental

Figure 2: **Combinations of ambient temperature and humidity under which sustainable cooling strategies have been assessed**
To contextualise these conditions, the hottest 2 hourly outdoor ambient temperature and associated relative humidity recorded in 110 global cities since Jan 1, 2007, are provided. Thermal strain is core temperature, cardiovascular strain is heart rate or rate-pressure product, and dehydration is body-mass loss. Grey boxes represent no data. Young adults are aged 18–35 years; older adults are older than 60 years. *Exercise performance studies were not included.

(aged 18–40 years), 38°C for older, healthy adults (aged >65 years), and 37°C for older adults taking anti-cholinergic medications. How physiological heat strain is altered by fan use with progressive dehydration from multiple heat exposure days, or by the use of medications or drugs that potentially alter thermoregulatory capacity is unknown.[1]

Evaporative and conductive properties of water can be exploited to elicit body cooling in extreme heat without the use of air conditioning or fans (table). Intermittently applying cool tap water (about 20°C) to large skin surface areas (self-dousing) reduces cardiovascular strain and alleviates thermal discomfort in both hot and humid and very hot, dry conditions and reduces dehydration by up to 65%.[54] Foot immersion in about 20°C water also improves thermal comfort and dehydration in hot-humid conditions,[54] whereas immersing the hands and forearms in about 10°C water moderates core temperature elevations during intermittent exercise under similar conditions.[55,62] As cooling strategies with about 20°C water do not require electricity, self-dousing and, to a lesser extent, cold water foot immersion can be recommended during unplanned blackouts or in settings without any electricity supply, if water supply is preserved and available. Notably, such strategies are not currently included in public health messaging for health protection during heat extremes.

Forcing air across a wet membrane can cool air by extracting latent heat energy. Large volume mechanical evaporative coolers can theoretically reduce air temperature by 15–20°C in hot and dry climates,[63] but cooling power is vastly diminished in hot and humid conditions, and in tropical and subtropical regions, evaporative coolers without proper maintenance can become mosquito breeding sites. Although capital costs are less than air conditioning costs, they can remain prohibitively expensive for some people. A wet sheet across an open window or electric fan can serve as ad-hoc evaporative coolers. Little evidence exists that these approaches alter physiological strain in heat extremes. Cooling will be limited by the relatively small surface area for evaporation and a low capacity to hold moisture, while natural convection through windows will be disrupted. Misting fans cool surrounding air but must be operated in well ventilated or outdoor areas otherwise humidity increases offset any benefit of lower air temperatures. Conductive cooling with crushed ice wrapped in damp towels (so-called ice towels) applied to the neck and chest attenuates physiological and perceptual heat strain during intermittent exercise in both hot, humid[53] and very hot, dry[57] conditions (figure 2, table). A crushed ice and water mix or cold water drink provides internal cooling, but parallel reductions in sweating mediated by independent abdominal thermoreceptors proportionally reduces skin surface evaporation.[64] Consequently, the temperature of drinks if ingested when a person has already started sweating does not affect body temperature.[65]

Breaks in physical activity reduce metabolic heat production and provide opportunities to apply other cooling strategies, such as removing clothing, and rehydrating. Work-to-rest ratios prescribed for decades to reduce health risks in hot occupational environments[66] can blunt rises in core temperature; however, their effectiveness might need to be re-evaluated with increasingly hotter weather. The sudden removal of lower leg muscle contractions alongside high amounts of skin blood flow can cause post-exercise hypotension and an elevated risk of syncope.[67] Shelter should be sought from other heat sources (eg, sun) during breaks when possible.

Considerations and opportunities for applying sustainable cooling strategies in heat-vulnerable settings

Aged care homes

Occupants usually have medical conditions and take multiple medications that can collectively reduce heat resilience.[1] Behavioural adaptive capacity is often reduced in older adults, particularly if they have less mobility or neurodegenerative diseases such as dementia, and clothing is often chosen according to cultural norms rather than for optimal heat loss. Given the large variability in vulnerability factors among those living in aged care homes, lowering indoor temperatures should be prioritised (panel 2).[68] Interventions at the individual level are also considered most important by care managers for heat stress reduction.[92]

Slums

Construction materials of slum dwellings such as corrugated iron substantially contribute to oppressively hot indoor daytime temperatures (panel 2).[70] Poor water quality and sanitation remains commonplace in slums; therefore, heat can secondarily increase the risk of waterborne diseases,[70] particularly given that the leading recommendation advocated by public health authorities is to drink water during heat extremes and hot weather. If point-of-use decontamination methods, such as filtering through charcoal, do not clean water sufficiently for drinking, water might still be treated to be safe enough to be applied to the skin.

Workplaces

Any cooling solutions in occupational settings should not interfere with the optimal completion of work tasks or exacerbate other health risks.[78,93] Workers often begin a shift dehydrated and maintain a depleted hydration status throughout the day.[94] Female workers might be reluctant to hydrate, trying to avoid using a toilet altogether due to unhygienic or absence of facilities.[76] Male workers older than 60 years also tend to ration drinks, worried about requirements for frequent toilet breaks. Personal protective equipment and clothing that reduces heat loss must often be worn in many workplaces. Outdoor workers also need to balance heat loss and ultraviolet protection requirements. Some jobs require fully encapsulated protective clothing (eg, asbestos removal, firefighters), therefore internal cooling systems are required. Limiting exposure time in such clothing and integrating other individual level cooling strategies is advisable (panel 2).[62,78,93]

Schools

In playgrounds, exposure to direct solar radiation and hot surfaces presents the greatest heat-related health risks. In classrooms, school building design requirements restrict cooling options. Individual level cooling strategies should be simple to implement without disrupting the learning environment. Opportunities for cooling by

Panel 2: Recommended sustainable cooling strategies during heat extremes and hot weather for heat vulnerable settings

Aged care homes

- Installing rooftop sprinklers, outdoor sunshades protecting common rooms, and heat-reflective window glass, using evaporative coolers, and ensuring adequate natural ventilation, should be prioritised to reduce indoor temperatures[68]
- Application of ice towels, reducing clothing coverage, and wearing a cotton t-shirt saturated with water[56] will provide effective body cooling
- Fans should only be used with parallel self-dousing at air temperatures above 38°C[61] due to lower sweat rates with advanced age[48,69]

Slums

- Substituting construction materials of slum dwellings, such as corrugated iron, with better insulated walls and roofs will reduce oppressively hot indoor daytime temperatures[70]
- Water that is not sufficiently clean to drink can be applied to the skin with a sponge (as opposed to spray) for self-dousing—evaporation of this water reduces the need to sweat[54] and could ultimately blunt thirst
- Other individual level heat coping strategies during the hottest times of the day can include cold water foot immersion, wearing a water-saturated t-shirt, seeking shade in well ventilated areas, doing higher intensity activities at cooler hours, and reducing clothing coverage

Workplaces

- Electric fans can improve manual work performance in most hot conditions,[71] but they impair wind-sensitive task performance, and in workplaces containing particulates or gases they might cause eye or respiratory problems; the development of user-controlled chairs with built-in low-energy fans might provide a safer alternative[72]
- Extra breaks should be given in relatively cool areas with access to water for drinking and self-dousing; indoors, well ventilated rooms can be used, whereas outdoors, temporary rest stations can be created with portable parasols and sun tents;[73] work shifts can be adjusted to avoid the hottest hours, or midday so-called siestas in cooler environments can be taken to avoid peak temperatures[74]
- Hydration monitoring via urine colour and volume can be used, as it is simple and effective[75]
- Industries with scarce supplies of clean water access (eg, agriculture), should provide workers with methods for carrying water (eg, backpacks containing water bladders),[73] periodically bring water to employees, or establish water caches around the work area and access to clean lavatory facilities[76]
- Very cold water and iced drinks have small and transient cooling effect during work[65] and are less palatable resulting in less consumption; water temperature for workers should ideally be maintained at about 10°C[77]
- Where whole-body protection (eg, against chemicals) is not required, ventilation patches in clothing can be used in less exposed areas, such as the groin, underarms, inside the elbows, and behind the knees; outdoor workers should wear long, loose-fitting, lightweight, breathable clothing, light in colour or with reflective fabrics
- For jobs requiring fully encapsulated protective clothing, phase-change materials or cooling systems with compressed cool air can be used but are expensive and carry a greater environmental impact[78]

Schools

- In playgrounds, shading ground materials and structures with trees and sails improves children's thermal comfort[79] and decreases surface temperatures;[80] adequate wind flow through appropriate landscape design supports sweat evaporation and evapotranspiration from grass and trees[81]
- In classrooms, body cooling can be achieved by reducing radiant influx and improving convective airflow with fans; active hydration policies (eg, allowing water bottles on desks throughout the day); water spray bottles for self-dousing can be effective but potentially impractical
- Flexibility in school uniform dress codes (eg, taking off ties, opening shirts) should be allowed

Mass gatherings

- Education from religious and community leaders is needed to improve compliance with protective behaviours during these events
- Access to sufficient drinking water and shaded cooling areas should be prioritised for all mass gatherings in hot weather[82]
- Adequate availability of heat prevention information (including signs with symptoms of heat illness, prevention, and treatment guidelines) should be provided
- Outdoor misting fans can be used[83]
- Scoring systems can also be helpful to predict the medical staff required for mass events[84]

(Continues on next page)

(Panel 2 continued from previous page)

Refugee camps
- Breathable tents
- Information on hygienic water and food preparation practices to prevent food and water-borne diseases
- Female medical aid workers should be available to check on female refugees[85]
- When non-potable, but otherwise safe, water is present, self-dousing can reduce sweating requirements, thereby slowing dehydration[54]

Sport
- Playing surfaces can be used that minimise heat retention and emitted radiation,[86] whereas playing areas can be built and oriented to permit sufficient natural ventilation and include easily accessible shelters that provide shade
- Precooling (before exercise) with cold water and crushed ice ingestion or immersion can reduce core temperature;[87] however, body temperature then rises quickly when exercise commences, so any benefits of precooling are transient[88]
- Precooling and percooling (during exercise) with ice vests, cold water ingestion, and the application of cooling packs, especially to the neck, can improve exercise performance [89]
- For sports with short but frequent breaks (eg, tennis), application of ice towels reduces physiological heat strain[57]
- For sports with near-continuous play separated by a prolonged midpoint break (eg, Association Football), self-dousing the skin or clothing, or misting fans reduce physiological heat strain;[90] extending halftime breaks, even if participants remain in the heat, reduces body temperature far more effectively than adding shorter (1–3 min) so-called quarter-time breaks[90]
- A 70 kg moderately fit person working at 50% of their maximum capacity at 35°C must exercise 1–1·5 h to reach this dehydration threshold; ad libitum water ingestion replaces about 50% of sweat losses during exercise in the heat,[91] so this time is approximately doubled if water is readily available at all times

introducing flexibility in school uniform dress codes and recess times should also be considered (panel 2).

Mass gatherings
Heat exhaustion and dehydration are the most common medical presentations at mass gatherings in hot weather.[82] Over the next 15 years, the Hajj pilgrimage (Mecca, Saudi Arabia), with more than 7 million annual participants, will take place during months with mean daily high temperatures of more than 40°C. Risk of heat-related illness is exacerbated by age, comorbidities such as diabetes,[95] and reluctance among some people to adopt hydration and other preventative practices (eg, umbrellas) due to misconceptions about compatibility with Hajj rituals.[96]

Refugee camps
Similar challenges to mass gatherings present themselves at refugee camps, but with shorter time to prepare for hot weather and heat extremes, fewer trained personnel, and less resources and electricity.[85,97] Women in refugee camps can be at a greater risk of heat-related illness due to segregation in insulative tents, and further restrictions to food, water, and medical care.[85]

Sport
Very hot, artificial, playing surfaces and local micro-climates created by surrounding structures are a leading contributor to the elevated risk of heat stress of people playing sport.[86] Individual level cooling strategies to mitigate risk of heat stress during hot weather can be applied before or during exercise. The effectiveness during exercise is dependent on how a particular sport is structured, and thus the opportunities to intervene. Some sports consist of short but frequent breaks (eg, tennis) during which aggressive cooling manoeuvres can be quickly applied and removed (panel 2).[57] Other sports have near-continuous play separated by a prolonged midpoint break (eg, Association Football). Sweat losses of more than 2% of total bodyweight exacerbates the risk of exertional heat illness[98,99] and should be avoided. On the basis of a consensus statement from the American College of Sports Medicine,[100] providing facilities for fast, emergency body cooling (eg, ice baths) during hot weather events is a proven lifesaving safety feature. Allowing sports participants to progressively adapt physiologically to the heat is an effective way to reduce heat strain. For maximal adaptations to occur, daily exposures to summer weather with graded increases in exercise intensity, and if necessary, modifications to protective equipment and clothing worn, are required across the course of 1–2 weeks.[101] Ultimately the suspension or cancellation of play can be mandated if the risk is deemed sufficiently high. The amount of heat stress judged as acceptable is highly dependent on the level of competition and profile of the competitor (eg, highly trained professional adult *vs* recreational junior). Scheduling of professional sports is strongly driven by commercial interests, including broadcasting rights. At the community level, there might be a reluctance, or insufficient flexibility, to reschedule matches due to a restricted availability of playing facilities.

Heat action plans
Many jurisdictions have adopted action plans and associated measures to protect human health during bouts of extreme heat.[102,103] Many heat action plans, also known as heat–health action plans,[104] have common elements: early warning to the public that integrates surveillance of health outcomes with weather forecast information; roles and

responsibilities from local to national levels for actions in the plan; direction for communicating to the public and stakeholders to implement heat alerts and support broader heat-related health education; community level response measures to protect vulnerable populations (eg, health promotion, portable water stations, and outreach to vulnerable populations); advice on longer-term preventative measures to reduce risks (eg, reducing the urban heat island through urban planning); and measures for evaluating the plan to support iterative improvements to the elements over time.[102,105–107] Wide variation in heat action plans exists around scope, partner engagement, public health interventions to reduce risks, and target populations for outreach because of differences in capacity, extreme heat planning processes, and local meteorological conditions (figure 3).

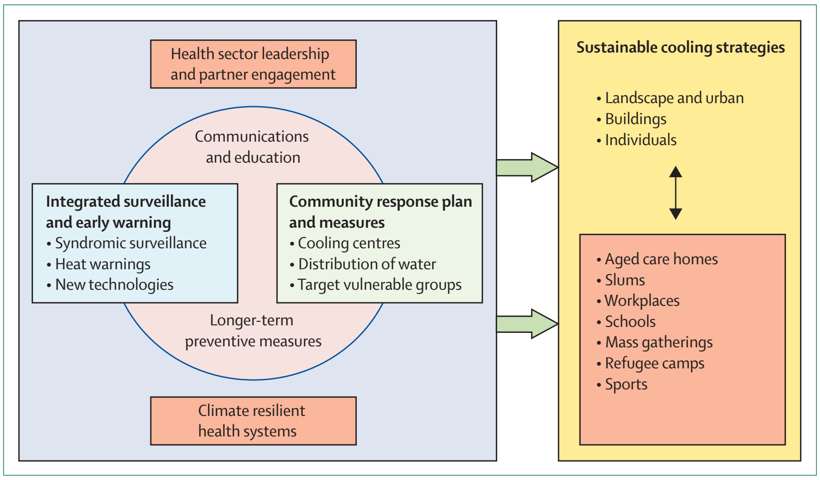


Figure 3: **Community heat action plan elements and preventative actions to reduce heat-related health risks**

Integrated early warning and surveillance

Heat action plans should be tailored to local needs and developed on the basis of the latest evidence of risks to health and of effective protective measures that can be readily implemented by public health officials and the public. They require robust surveillance and monitoring of heat-related morbidity and mortality to support early warning of impending heat events. Thresholds for issuing heat warnings, and to activate community response measures during heat extremes (eg, open cooling centres and distribution of water), should be based on evidence of impacts on health and systems.[102,105] This approach can reduce the risk of false negatives whereby the public receives too many warnings and the uptake of protective behaviours declines. Thresholds are generally established in collaboration with health professionals, meteorologists, and representatives of other key stakeholder groups (including those representing the most vulnerable), while accounting for the local-specific context. Real-time or syndromic surveillance of heat-related health outcomes from health facilities provides public health officials with information on morbidity and mortality during heat extremes to support decisions respecting the warning (eg, whether to initiate a warning or increase the level) and the response (eg, where and who to target outreach by health professionals and caregivers). Researchers from the University of North Carolina at Chapel Hill and the Southeast Regional Climate Center in North Carolina, USA, developed an instrument that is used to predict the incidence of heat-related illness (ie, emergency room visits) on the basis of weather forecasts of maximum daily temperature. Public health officials use predictions to send heat warnings to community stakeholders and vulnerable groups that advise the public about cooling centres and other opportunities to take protective measures.[108] New technological developments and applications (eg, smartphones and social media) will create opportunities to improve surveillance and early warning activities, including for low resource and remote settings.[109–111] However, the availability of information (eg, temperature–mortality associations) needed to develop heat action plans varies widely among communities within and across countries (eg, low-income and middle-income countries), constituting an important knowledge gap.

Communications and education

Researchers and public health authorities have been advocating for efforts to educate people about the dangers to health from heat events for at least four decades.[112–116] Heat action plans require well defined communication goals, strategies, products, and messages to increase awareness of health risks and protective measures among the public, community stakeholders, and caregivers before, during, and after heat extremes.[102,117] Communications activities should be tailored to the needs of specific populations and settings, such as caregivers,[118–121] high school athletes who exercise in hot conditions,[101,122,123] dangers of heat stroke among children left in parked cars,[124,125] and mass gatherings.[126,127]

Promoting the adoption of protective measures faces many challenges. Knowledge of heat-related health risks and awareness of heat warnings does not always lead to effective personal protective actions.[128–130] Heat-related health communication activities are most effective when they address challenges that prevent information about reducing health risks from reaching the most vulnerable populations and any broader difficulties these populations face, such as tourists or newcomers to a country who face language barriers.[131]

As heat action plans evolve with increasingly frequent and severe heat extremes, communications approaches and tools will need to change as well. For example, innovative ways of communicating heat-related health risks for decision making, such as geospatial mapping with real-time health surveillance,[132–134] might be used to help manage increasing climate change risks from

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multiple and compounding climate hazards. New technology development and the expansion of existing ones (eg, smart homes, multi-sensors for monitoring individuals in their home, individual health trackers and homecare-based ambient trackers, and automated environmental control) have the potential to facilitate future adaptation to heat extremes.[135]

Climate-resilient health systems

Health systems are crucial for protecting people from climate-related risks through preventative (eg, reducing greenhouse gas emissions), primary (eg, urban planning and heat action plans), secondary (eg, surveillance of impacts), and tertiary actions (eg, correctly diagnosing and treating heat illness). Health systems, including health facilities, programmes, and health professionals, can be vulnerable to climate hazards like heat extremes when staff and their families are affected, essential supplies and operations (eg, food, water, and energy) are also affected, and demand for patient services outstrips capacity to respond.[136,137] The climate resilience of health systems is increased through actions that improve health information services, for example, by conducting vulnerability and adaptation assessments and climate stress tests, enhancing monitoring and surveillance of health impacts, investing new technologies and infrastructures, and improving health services by training staff and mainstreaming climate change into relevant operations and planning activities.[137,138] The SA Extreme Heat Strategy[139] includes information on people at risk from extreme heat events and a mental health service clinician heatwave checklist to assess the readiness of people with mental health issues to take protective measures during an event.

Evaluation for continuous improvement

The effectiveness of heat action plans is evaluated through scientific studies, led by public health agencies through regular programme evaluation mechanisms (eg, end of heat season workshops and table-top simulation exercises)[107] and as part of broader climate change and health assessments.[106,138] Evidence suggests these plans can reduce risks to health through public education and awareness actions,[140–142] surveillance and monitoring of effects,[143–146] mobilising of community resources, such as opening cooling centres,[147] and cooling communities through urban design and modifications to infrastructures.[148] A 2018 study attributed a dramatic decline in heat-related mortality among people living in Ahmedabad, India, from similarly intense heat extremes occurring in 2010 and in 2015.[149] However, other studies have suggested that some heat action plans have had little effect on health outcomes; more research is needed to examine efficacy of different systems and approaches.[150] As health threats from heat extremes continue to grow, with an estimated 54% of the global population exposed to more than 20 days of dangerous heat per year by 2100 at 2°C warming (GCA, 2019), heat action plans linked to efforts to enhance health system resilience will become increasingly important for protecting populations. The success of these plans in preparing individuals and communities will depend on iterative improvements to activities on the basis of regular evaluation of the efforts to protect health in future climates and from current climate variability.[106,151]

Conclusion

The health impacts of extreme heat exposure are already pronounced for many. Even with optimum mitigation of greenhouse gas emissions, human activity has set a future climate change trajectory that will inevitably lead to far worse exposure to extreme heat than the present day for much of the planet's population. The health impacts will be concentrated, as they are now, among populations and regions where the risks are largely unnoticed and inadequately addressed: older people (>65 years); those with comorbidities such as cardiovascular disease, diabetes, and renal disease; and people with lower socioeconomic status. Excessive heat in workplaces is a serious health hazard for employees across a range of industry sectors. Employers also pay a heavy price through lost productivity due to reductions in cognitive and physical work performance, and large increases in sick leave. Society must adapt in ways that not only enable it to survive, but thrive, in a much hotter future. Therefore, the global community and policy makers should look beyond short-term solutions that might be convenient but do not promote long-term resilience. For example, mechanically cooling indoor, and even outdoor, living and working spaces with air conditioning reduces heat stress. However, air conditioning is inaccessible to many people due to the cost, and the high electricity requirements of mechanical cooling result in substantial emissions of greenhouse gas emissions.

This Series paper describes opportunities for implementing cheaper and far more sustainable cooling strategies at the landscape and urban, building, and individual levels and summarises the benefits and limitations of each strategy (table). The effectiveness of different strategies depends on their compatibility with a particular setting. For example, the recommended solution for an older person in a poorly insulated high-rise apartment in New York will be different to the optimal strategy for a young worker in a ready-made garment factory in Dhaka, Bangladesh, or an elite football player competing outdoors in Doha, Qatar. Recommended sustainable cooling strategies for settings in which the health risks of extreme heat exposure are commonly high are given in panel 2. Irrespective of the setting, recommended actions should be driven by the latest scientific evidence and not conventional wisdom that was developed during cooler periods. The integration of this information into heat action plans, which include early warning systems supported by robust surveillance and monitoring, and the mobilisation of community resources can improve their effectiveness in reducing negative health outcomes in future heat extremes. New technological advancements and applications will create opportunities for the targeted delivery of customised evidence-based early warning activities to the most vulnerable in low-resource and remote settings.

Contributors

OJ conceptualised this Series paper and led the organisation, drafting, and finalising of the paper. OJ and NBM contributed to the development of the table, panel 2, and figures 1 and 2. KLE and AC contributed to the conceptualisation of this Series paper. AM and RdD contributed to the development of panel 1. PB led the development of figure 3. All authors contributed to the writing, editing, and finalising of the paper, and reviewed and approved the final version.

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References

1 Ebi KL, Capon A, Berry P, et al. Hot weather and heat extremes: health risks. *Lancet* 2021; **398:** 698–708.
2 Coates L, Haynes K, O'Brien J, McAneney J, De Oliveira FD. Exploring 167 years of vulnerability: an examination of extreme heat events in Australia 1844–2010. *Environ Sci Policy* 2014; **42:** 33–44.
3 Rey G, Fouillet A, Bessemoulin P, et al. Heat exposure and socio-economic vulnerability as synergistic factors in heat-wave-related mortality. *Eur J Epidemiol* 2009; **24:** 495–502.
4 Kilbourne EM, Choi K, Jones TS, Thacker SB. Risk factors for heatstroke: a case-control study. *JAMA* 1982; **247:** 3332–36.
5 Flouris AD, Dinas PC, Ioannou LG, et al. Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Health* 2018; **2:** e521–31.
6 Smith KR, Woodward A, Lemke B, et al. The last Summer Olympics? Climate change, health, and work outdoors. *Lancet* 2016; **388:** 642–44.
7 Lange S, Volkholz J, Geiger T, et al. Projecting exposure to extreme climate impact events across six event categories and three spatial scales. *Earths Future* 2020; **11:** e2020EF001616.
8 Intergovernmental Panel on Climate Change. Summary for policymakers. In: Masson-Delmotte VP, Zhai H-O, Pörtner D, et al, eds. Special report: global warming of 1·5°C. 2018. https://www.ipcc.ch/sr15/chapter/spm/ (accessed July 21, 2021).
9 Jay O, Capon A. Use of physiological evidence for heatwave public policy. *Lancet Planet Health* 2018; **2:** e10.
10 Khosla R, Miranda ND, Trotter PA, et al. Cooling for sustainable development. *Nat Sustain* 2020; **4:** 1–8.
11 International Energy Agency. The future of cooling. 2018. https://www.iea.org/reports/the-future-of-cooling (accessed March 4, 2020).
12 Bouchama A, Dehbi M, Mohamed G, Matthies F, Shoukri M, Menne B. Prognostic factors in heat wave–related deaths: a meta-analysis. *Arch Intern Med* 2007; **167:** 2170–76.
13 Nunes B, Paixão E, Dias CM, Nogueira P, Falcão JM. Air conditioning and intrahospital mortality during the 2003 heatwave in Portugal: evidence of a protective effect. *Occup Environ Med* 2011; **68:** 218–23.
14 Seppänen O, Fisk WJ. A model to estimate the cost-effectiveness of improving office work through indoor environmental control. *ASHRAE Trans* 2005; **111:** 663–72.
15 Porras-Salazar JA, Wyon DP, Piderit-Moreno B, Contreras-Espinoza S, Wargocki P. Reducing classroom temperature in a tropical climate improved the thermal comfort and the performance of elementary school pupils. *Indoor Air* 2018; **28:** 892–904.
16 Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press, 1970.
17 ASHRAE. Thermal comfort. In: ASHRAE, eds. Fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, 2009: 9.1–9.30.
18 ASHRAE. Thermal environmental conditions for human occupancy. ANSI/ASHRAE standard 55–2017 (supersedes ANSI/ASHRAE standard 55–2013) includes ANSI/ASHRAE addenda listed in appendix N. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, 2017.
19 Parkinson T, de Dear R, Brager G. Nudging the adaptive thermal comfort model. *Energy Build* 2020; **206:** 109559.
20 Waite M, Cohen E, Torbey H, Piccirilli M, Tian Y, Modi V. Global trends in urban electricity demands for cooling and heating. *Energy* 2017; **127:** 786–802.
21 Broome RA, Smith WT. The definite health risks from cutting power outweigh possible bushfire prevention benefits. *Med J Aust* 2012; **197:** 440.
22 Anderson GB, Bell ML. Lights out: impact of the August 2003 power outage on mortality in New York, NY. *Epidemiology* 2012; **23:** 189.
23 Salamanca F, Georgescu M, Mahalov A, Moustaoui M, Wang M. Anthropogenic heating of the urban environment due to air conditioning. *J Geophys Res Atmos* 2014; **119:** 5949–65.
24 International Energy Agency. Cooling. 2020. https://www.iea.org/reports/cooling (accessed March 4, 2020).
25 International Energy Agency. Global CO_2 emissions in 2019. 2020. https://www.iea.org/articles/global-co2-emissions-in-2019 (accessed March 4, 2020).
26 Harlan SL, Brazel AJ, Prashad L, Stefanov WL, Larsen L. Neighborhood microclimates and vulnerability to heat stress. *Soc Sci Med* 2006; **63:** 2847–63.
27 China NBoSo. Fourteenth of a series of achievements in economic and social development on the 70th anniversary of the founding of new China. 2018. http://www.stats.gov.cn/tjsj/zxfb/201908/t20190809_1690098.html (accessed Dec 8, 2020; in Chinese).
28 White-Newsome JL, Sánchez BN, Jolliet O, et al. Climate change and health: indoor heat exposure in vulnerable populations. *Environ Res* 2012; **112:** 20–27.
29 Oke TR. Boundary layer climates. London: Routledge, 2002.
30 Vanos JK, Warland JS, Gillespie TJ, Slater GA, Brown RD, Kenny NA. Human energy budget modeling in urban parks in Toronto and applications to emergency heat stress preparedness. *J Appl Meteorol Climatol* 2012; **51:** 1639–53.
31 Zhang Y, Murray AT, Turner Ii B. Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona. *Landsc Urban Plan* 2017; **165:** 162–71.
32 Bevilacqua P, Mazzeo D, Bruno R, Arcuri N. Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate. *Energy Build* 2017; **150:** 318–27.
33 Herath H, Halwatura R, Jayasinghe G. Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban For Urban Green* 2018; **29:** 212–22.
34 Krayenhoff ES, Moustaoui M, Broadbent AM, Gupta V, Georgescu M. Diurnal interaction between urban expansion, climate change and adaptation in US cities. *Nat Clim Chang* 2018; **8:** 1097–103.
35 Zimmerman R, Brenner R, Llopis Abella J. Green infrastructure financing as an imperative to achieve green goals. *Climate* 2019; **7:** 39.

36 Ng E. Policies and technical guidelines for urban planning of high-density cities–air ventilation assessment (AVA) of Hong Kong. *Build Environ* 2009; **44:** 1478–88.

37 Hart MA, Sailor DJ. Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theor Appl Climatol* 2009; **95:** 397–406.

38 Mandal J, Fu Y, Overvig AC, et al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. *Science* 2018; **362:** 315–19.

39 Baniassadi A, Sailor DJ, Ban-Weiss GA. Potential energy and climate benefits of super-cool materials as a rooftop strategy. *Urban Clim* 2019; **29:** 100495.

40 Muselli M. Passive cooling for air-conditioning energy savings with new radiative low-cost coatings. *Energy Build* 2010; **42:** 945–54.

41 Erell E, Pearlmutter D, Boneh D, Kutiel PB. Effect of high-albedo materials on pedestrian heat stress in urban street canyons. *Urban Clim* 2014; **10:** 367–86.

42 Hardin A, Vanos J. The influence of surface type on the absorbed radiation by a human under hot, dry conditions. *Int J Biometeorol* 2018; **62:** 43–56.

43 Taleghani M, Sailor D, Ban-Weiss GA. Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. *Environ Res Lett* 2016; **11:** 024003.

44 Brown RD. Design with microclimate: the secret to comfortable outdoor space. Washington, DC: Island Press, 2010.

45 Sadeghi M, de Dear R, Wood G, Samali B. Development of a bioclimatic wind rose tool for assessment of comfort wind resources in Sydney, Australia for 2013 and 2030. *Int J Biometeorol* 2018; **62:** 1963–72.

46 Ravanelli NM, Hodder SG, Havenith G, Jay O. Heart rate and body temperature responses to extreme heat and humidity with and without electric fans. *JAMA* 2015; **313:** 724–25.

47 Morris NB, English T, Hospers L, Capon A, Jay O. The effects of electric fan use under differing resting heat index conditions: a clinical trial. *Ann Intern Med* 2019; **171:** 675–77.

48 Gagnon D, Romero SA, Cramer MN, Jay O, Crandall CG. Cardiac and thermal strain of elderly adults exposed to extreme heat and humidity with and without electric fan use. *JAMA* 2016; **316:** 989–91.

49 Smith CJ, Alexander LM, Kenney WL. Nonuniform, age-related decrements in regional sweating and skin blood flow. *Am J Physiol Regul Integr Comp Physiol* 2013; **305:** R877–85.

50 Wright Beatty HE, Hardcastle SG, Boulay P, Flouris AD, Kenny GP. Increased air velocity reduces thermal and cardiovascular strain in young and older males during humid exertional heat stress. *J Occup Environ Hyg* 2015; **12:** 625–34.

51 Hailes WS, Cuddy JS, Cochrane K, Ruby BC. Thermoregulation during extended exercise in the heat: comparisons of fluid volume and temperature. *Wilderness Environ Med* 2016; **27:** 386–92.

52 Selkirk GA, McLellan TM, Wong J. Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. *J Occup Environ Hyg* 2004; **1:** 521–31.

53 Schranner D, Scherer L, Lynch GP, et al. In-play cooling interventions for simulated match-play tennis in hot/humid conditions. *Med Sci Sports Exerc* 2017; **49:** 991–98.

54 Morris NB, Gruss F, Lempert S, et al. A preliminary study of the effect of dousing and foot immersion on cardiovascular and thermal responses to extreme heat. *JAMA* 2019; **322:** 1411–13.

55 Giesbrecht GG, Jamieson C, Cahill F. Cooling hyperthermic firefighters by immersing forearms and hands in 10 degrees C and 20 degrees C water. *Aviat Space Environ Med* 2007; **78:** 561–67.

56 Cramer MN, Huang M, Moralez G, Crandall CG. Keeping older individuals cool in hot and moderately humid conditions: wetted clothing with and without an electric fan. *J Appl Physiol* 2020; **128:** 604–11.

57 Lynch GP, Périard JD, Pluim BM, Brotherhood JR, Jay O. Optimal cooling strategies for players in Australian Tennis Open conditions. *J Sci Med Sport* 2018; **21:** 232–37.

58 Baniassadi A, Sailor DJ, Krayenhoff ES, Broadbent AM, Georgescu M. Passive survivability of buildings under changing urban climates across eight US cities. *Environ Res Lett* 2019; **14:** 074028.

59 Rothfusz LP. The heat index "equation" (or, more than you ever wanted to know about heat index). Fort Worth, TX: National Oceanic and Atmospheric Administration, National Weather Service, Office of Meteorology, 1990; 9023.

60 United States Environmental Protection Agency. Excessive heat events guidebook. Washington, DC: US Environmental Protection Agency, 2006.

61 Morris NB, Chaseling GK, English T, et al. Electric fan use for cooling during hot weather: a biophysical modelling study. *Lancet Planet Health* 2021; **5:** e368–77.

62 DeGroot DW, Gallimore RP, Thompson SM, Kenefick RW. Extremity cooling for heat stress mitigation in military and occupational settings. *J Therm Biol* 2013; **38:** 305–10.

63 Watt J. Evaporative air conditioning handbook. Berlin: Springer Science & Business Media, 2012.

64 Morris NB, Coombs G, Jay O. Ice slurry ingestion leads to a lower net heat loss during exercise in the heat. *Med Sci Sports Exerc* 2016; **48:** 114–22.

65 Jay O, Morris NB. Does cold water or ice slurry ingestion during exercise elicit a net body cooling effect in the heat? *Sports Med* 2018; **48:** 17–29.

66 Malchaire J. The TLV work—rest regimens for occupational exposure to heat: a review of their development. *Ann Occup Hyg* 1979; **22:** 55–62.

67 Halliwill JR. Mechanisms and clinical implications of post-exercise hypotension in humans. *Exerc Sport Sci Rev* 2001; **29:** 65–70.

68 Ministerie van Volksgezondheid, Welzijn en Sport. Nationaal Hitteplan 2007. https://webcache.googleusercontent.com/search?q=cache:EXTFzfo1rNEJ:https://zoek.officielebekendmakingen.nl/kst-30800-XVI-158-b1.pdf+&cd=2&hl=en&ct=clnk&gl=dk (accessed Dec 18, 2020; in Dutch).

69 Greaney JL, Kenney WL, Alexander LM. Sympathetic regulation during thermal stress in human aging and disease. *Auton Neurosci* 2016; **196:** 81–90.

70 Ezeh A, Oyebode O, Satterthwaite D, et al. The history, geography, and sociology of slums and the health problems of people who live in slums. *Lancet* 2017; **389:** 547–58.

71 Jay O, Hoelzl R, Weets J, et al. Fanning as an alternative to air conditioning—a sustainable solution for reducing indoor occupational heat stress. *Energy Build* 2019; **193:** 92–98.

72 Watanabe S, Shimomura T, Miyazaki H. Thermal evaluation of a chair with fans as an individually controlled system. *Build Environ* 2009; **44:** 1392–98.

73 Bodin T, García-Trabanino R, Weiss I, et al. Intervention to reduce heat stress and improve efficiency among sugarcane workers in El Salvador: phase 1. *Occup Environ Med* 2016; **73:** 409–16.

74 Kjellstrom T, Holmer I, Lemke B. Workplace heat stress, health and productivity–an increasing challenge for low and middle-income countries during climate change. *Glob Health Action* 2009; **2:** 2047.

75 Kavouras SA. Assessing hydration status. *Curr Opin Clin Nutr Metab Care* 2002; **5:** 519–24.

76 Venugopal V, Rekha S, Manikandan K, et al. Heat stress and inadequate sanitary facilities at workplaces–an occupational health concern for women? *Glob Health Action* 2016; **9:** 31945.

77 Burdon CA, Johnson NA, Chapman PG, O'Connor HT. Influence of beverage temperature on palatability and fluid ingestion during endurance exercise: a systematic review. *Int J Sport Nutr Exerc Metab* 2012; **22:** 199–211.

78 Morris NB, Jay O, Flouris AD, et al. Sustainable solutions to mitigate occupational heat strain–an umbrella review of physiological effects and global health perspectives. *Environ Health* 2020; **19:** 1–24.

79 Buller DB, English DR, Buller MK, et al. Shade sails and passive recreation in public parks of Melbourne and Denver: a randomized intervention. *Am J Public Health* 2017; **107:** 1869–75.

80 Vanos JK, Middel A, McKercher GR, Kuras ER, Ruddell BL. Hot playgrounds and children's health: a multiscale analysis of surface temperatures in Arizona, USA. *Landscape Urban Plan* 2016; **146:** 29–42.

81 Kennedy E, Olsen H, Vanos J, Vecellio D. Thermally comfortable playgrounds: a review of literature and survey of experts—technical report. Ottawa, ON: Health Canada and Standards Council of Canada, 2020.

82 Soomaroo L, Murray V. Weather and environmental hazards at mass gatherings. *PLoS Curr* 2012; **4:** e4fca9ee30afc4.

83 Brennan RJ, Wetterhall SF, Williams RJ, et al. Medical and public health services at the 1996 Atlanta Olympic Games: an overview. *Med J Austr* 1997; **167:** 595–98.

84 Hartman N, Williamson A, Sojka B, et al. Predicting resource use at mass gatherings using a simplified stratification scoring model. *Am J Emerg Med* 2009; **27:** 337–43.

85 Rashid A, Adnan MN. Pakistan's refugees face uncertain. *Lancet* 2009; **374:** 13–14.

86 Pryor JL, Pryor RR, Grundstein A, Casa DJ. The heat strain of various athletic surfaces: a comparison between observed and modeled wet-bulb globe temperatures. *J Athl Train* 2017; **52:** 1056–64.

87 Bongers CC, Hopman MT, Eijsvogels TM. Cooling interventions for athletes: an overview of effectiveness, physiological mechanisms, and practical considerations. *Temperature* 2017; **4:** 60–78.

88 Morris NB, Chaseling GK, Bain AR, Jay O. Temperature of water ingested before exercise alters the onset of physiological heat loss responses. *Am J Physiol Regul Integr Comp Physiol* 2019; **316:** R13–20.

89 Bongers CCWG, Thijssen DHJ, Veltmeijer MTW, Hopman MTE, Eijsvogels TMH. Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. *Br J Sports Med* 2015; **49:** 377–84.

90 Chalmers S, Siegler J, Lovell R, et al. Brief in-play cooling breaks reduce thermal strain during football in hot conditions. *J Sci Med Sport* 2019; **22:** 912–17.

91 Greenleaf J, Brock P, Keil L, Morse J. Drinking and water balance during exercise and heat acclimation. *J Appl Physiol Respir Environ Exerc Physiol* 1983; **54:** 414–19.

92 Kunst AE, Britstra R. Implementation evaluation of the Dutch national heat plan among long-term care institutions in Amsterdam: a cross-sectional study. *BMC Health Serv Res* 2013; **13:** 135.

93 Morris NB, Levi M, Morabito M, et al. Health vs. wealth: employer, employee and policy-maker perspectives on occupational heat stress across multiple European industries. *Temperature* 2020: 1–18.

94 Piil JF, Lundbye-Jensen J, Christiansen L, et al. High prevalence of hypohydration in occupations with heat stress—perspectives for performance in combined cognitive and motor tasks. *PLoS One* 2018; **13:** e0205321.

95 Abdelmoety DA, El-Bakri NK, Almowalld WO, et al. Characteristics of heat illness during hajj: a cross-sectional study. *Biomed Res Int* 2018; **2018:** 5629474.

96 Yezli S, Mushi A, Yassin Y, Maashi F, Khan A. Knowledge, attitude and practice of pilgrims regarding heat-related illnesses during the 2017 Hajj mass gathering. *Int J Environ Res Public Health* 2019; **16:** 3215.

97 WHO. Migration and health: key issues. 2019. http://www.euro.who.int/en/health-topics/health-determinants/migration-and-health/migrant-health-in-the-european-region/migration-and-health-key-issues (accessed Feb 11, 2020).

98 Montain SJ, Coyle EF. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J Appl Physiol* 1992; **73:** 1340–50.

99 Sawka MN, Cheuvront SN, Kenefick RW. Hypohydration and human performance: impact of environment and physiological mechanisms. *Sports Med* 2015; **45:** 51–60.

100 Armstrong L, Casa D, Millard-Stafford M, et al. American College of Sports Medicine position stand. Exertional heat illness during training and competition. *Med Sci Sports Exerc* 2007; **39:** 556–72.

101 Kerr ZY, Register-Mihalik JK, Pryor RR, et al. The association between mandated preseason heat acclimatization guidelines and exertional heat illness during preseason high school American football practices. *Environ Health Perspect* 2019; **127:** 047003.

102 McGregor GR, Bessmoulin P, Ebi K, Menne B. Heatwaves and health: guidance on warning-system development. Geneva: World Meteorological Organization and World Health Organization, 2015.

103 Lee V, Zermoglio F, Ebi KL, Chemonics International. Heat waves and human health: emerging evidence and experience to inform risk management in a warming world. Washington, DC: United States Agency for International Development, 2019.

104 Koppe C, Kovats RS, Menne B, Jendritzky G, Wetterdienst D, WHO. Heat-waves: risks and responses. Copenhagen: World Health Organization Regional Office for Europe, 2004.

105 Singh R, Arrighi J, Jjemba E, Strachan K, Spires M, Kadihasanoglu A. Heatwave guide for cities. The Hague: Red Cross Red Crescent Climate Centre, 2019.

106 Hess JJ, Ebi KL. Iterative management of heat early warning systems in a changing climate. *Ann NY Acad Sci* 2016; **1382:** 21–30.

107 Health Canada. Heat alert and response systems to protect health: best practices guidebook. 2012. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/climate-change-health/heat-alert-response-systems-protect-health-best-practices-guidebook.html (accessed March 4, 2020).

108 Brainerd L, Ward A. Developing an early warning system to prevent heat illness. US Climate Resilience Toolkit. Washington, DC: US Federal Government, 2018.

109 De Perez EC, Van Aalst M, Bischiniotis K, et al. Global predictability of temperature extremes. *Environ Res Lett* 2018; **13:** 054017.

110 Green HK, Edeghere O, Elliot AJ, et al. Google search patterns monitoring the daily health impact of heatwaves in England: how do the findings compare to established syndromic surveillance systems from 2013 to 2017? *Environ Res* 2018; **166:** 707–12.

111 Jung J, Uejio CK, Duclos C, Jordan M. Using web data to improve surveillance for heat sensitive health outcomes. *Environ Health* 2019; **18:** 59.

112 Morgan P. Running into danger: heat stroke in competing runners. *Can Med Assoc J* 1980; **122:** 1113.

113 Zal HA. Recommended program for employees exposed to extremes of heat. *Occup Health Nurs* 1984; **32:** 293–96.

114 Ballester J, Harchelroad F. Hyperthermia: how to recognize and prevent heat-related illnesses. *Geriatrics* 1999; **54:** 20–23.

115 Kovats RS, Hajat S. Heat stress and public health: a critical review. *Annu Rev Public Health* 2008; **29:** 41–55.

116 van Loenhout JAF, Guha-Sapir D. How resilient is the general population to heatwaves? A knowledge survey from the ENHANCE project in Brussels and Amsterdam. *BMC Res Notes* 2016; **9:** 499.

117 Climate Bureau. Communicating the health risks of extreme heat events: toolkit for public health and emergency management officials. Ottawa, ON: Health Canada, 2011.

118 Herrmann A, Sauerborn R. General practitioners' perceptions of heat health impacts on the elderly in the face of climate change—a qualitative study in Baden-Württemberg, Germany. *Int J Environ Res Public Health* 2018; **15:** 843.

119 Westphal S, Childs R, Seifert K, et al. Managing diabetes in the heat: potential issues and concerns. *Endocr Pract* 2010; **16:** 506–11.

120 Abrahamson V, Wolf J, Lorenzoni I, et al. Perceptions of heatwave risks to health: interview-based study of older people in London and Norwich, UK. *J Public Health* 2009; **31:** 119–26.

121 The Lancet. Health professionals: be prepared for heatwaves. *Lancet* 2015; **386:** 219.

122 Allen SB, Cross KP. Out of the frying pan, into the fire: a case of heat shock and its fatal complications. *Pediatr Emerg Care* 2014; **30:** 904–10.

123 Whipple MT, Baggish AL, Pieroth EM, Chiampas GT. The three H's: head, heart, and heat considerations in soccer. *Am J Orthop* 2018; published online Oct 1. https://doi.org/10.12788/ajo.2018.0087.

124 Adato B, Dubnov-Raz G, Gips H, Heled Y, Epstein Y. Fatal heat stroke in children found in parked cars: autopsy findings. *Eur J Pediatr* 2016; **175:** 1249–52.

125 Mangus CW, Canares TL. Heat-related illness in children in an era of extreme temperatures. *Pediatr Rev* 2019; **40:** 97–107.

126 Nakamura S, Wada K, Yanagisawa N, Smith DR. Health risks and precautions for visitors to the Tokyo 2020 Olympic and Paralympic Games. *Travel Med Infect Dis* 2018; **22:** 3–7.

127 Grant WD, Nacca NE, Prince LA, Scott JM. Mass-gathering medical care: retrospective analysis of patient presentations over five years at a multi-day mass gathering. *Prehosp Disaster Med* 2010; **25:** 183–87.

128 Sheridan SC. A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness. *Int J Biometeorol* 2007; **52:** 3–15.

129 Lam M, Krenz J, Palmández P, et al. Identification of barriers to the prevention and treatment of heat-related illness in Latino farmworkers using activity-oriented, participatory rural appraisal focus group methods. *BMC Public Health* 2013; **13:** 1004.

130 Lane K, Wheeler K, Charles-Guzman K, et al. Extreme heat awareness and protective behaviors in New York City. *J Urban Health* 2014; **91:** 403–14.

131 Ebi K. Towards an early warning system for heat events. *J Risk Res* 2007; **10:** 729–44.

132 Toutant S, Gosselin P, Bélanger D, Bustinza R, Rivest S. An open source web application for the surveillance and prevention of the impacts on public health of extreme meteorological events: the SUPREME system. *Int J Health Geogr* 2011; **10:** 39.

133 Conlon K, Maxwell S, Rommel R, Sampson N, Jacquez G, O'Neill M. O-174: communicating heat-health vulnerability in preparation for heat events development and assessment of Internet-based Heat Evaluation and Assessment Tool (I-HEAT). *Epidemiology* 2012; **23:** S231.

134 Houghton A, Prudent N, Scott III JE, Wade R, Luber G. Climate change-related vulnerabilities and local environmental public health tracking through GEMSS: a web-based visualization tool. *Appl Geogr* 2012; **33:** 36–44.

135 M Bublitz F, Oetomo A, S Sahu K, et al. Disruptive technologies for environment and health research: an overview of artificial intelligence, blockchain, and internet of things. *Int J Env Res Public Health* 2019; **16:** 3847.

136 Balbus J, Berry P, Brettle M, et al. Enhancing the sustainability and climate resiliency of health care facilities: a comparison of initiatives and toolkits. *Rev Panam Salud Pública* 2016; **40:** 174–80.

137 Ebi KL, Berry P, Hayes K, et al. Stress testing the capacity of health systems to manage climate change-related shocks and stresses. *Int J Env Res Public Health* 2018; **15:** 2370.

138 WHO. Operational framework for building climate resilient health systems. Geneva: World Health Organization, 2015.

139 Government of South Australia. SA health extreme heat strategy. Adelaide, SA: Government of South Australia, 2016.

140 Oakman T, Byles-Drage H, Pope R, Pritchard J. Beat the heat: don't forget your drink—a brief public education program. *Aust NZ J Public Health* 2010; **34:** 346–50.

141 Nitschke M, Krackowizer A, Hansen AL, Bi P, Tucker GR. Heat health messages: a randomized controlled trial of a preventative messages tool in the older population of South Australia. *Int J Env Res Public Health* 2017; **14:** 992.

142 Kyselý J, Plavcová E. Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? *Clim Change* 2012; **113:** 437–53.

143 Elliot AJ, Bone A, Morbey R, et al. Using real-time syndromic surveillance to assess the health impact of the 2013 heatwave in England. *Environ Res* 2014; **135:** 31–36.

144 Perry AG, Korenberg MJ, Hall GG, Moore KM. Modeling and syndromic surveillance for estimating weather-induced heat-related illness. *J Environ Public Health* 2011; **2011:** 750236.

145 Josseran L, Caillère N, Brun-Ney D, et al. Syndromic surveillance and heat wave morbidity: a pilot study based on emergency departments in France. *BMC Med Inform Decis Mak* 2009; **9:** 14.

146 Commission for Environmental Cooperation. A guide for syndromic surveillance for heat-related health outcomes in North America. Montreal, QC: Commission for Environmental Cooperation, 2017: 48.

147 Widerynski S, Schramm PJ, Conlon KC, et al. Use of cooling centers to prevent heat-related illness: summary of evidence and strategies for implementation. Atlanta, GA: Centers for Disease Control and Prevention, 2017.

148 Hatvani-Kovacs G, Belusko M, Skinner N, Pockett J, Boland J. Drivers and barriers to heat stress resilience. *Sci Total Environ* 2016; **571:** 603–14.

149 Hess JJ, Lm S, Knowlton K, et al. Building resilience to climate change: pilot evaluation of the impact of India's first heat action plan on all-cause mortality. *J Environ Public Health* 2018; **2018:** 7973519.

150 Weinberger KR, Zanobetti A, Schwartz J, Wellenius GA. Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities. *Environ Int* 2018; **116:** 30–38.

151 Haines A, Ebi K. The imperative for climate action to protect health. *N Engl J Med* 2019; **380:** 263–73.