Climate change, environmental extremes, and human health

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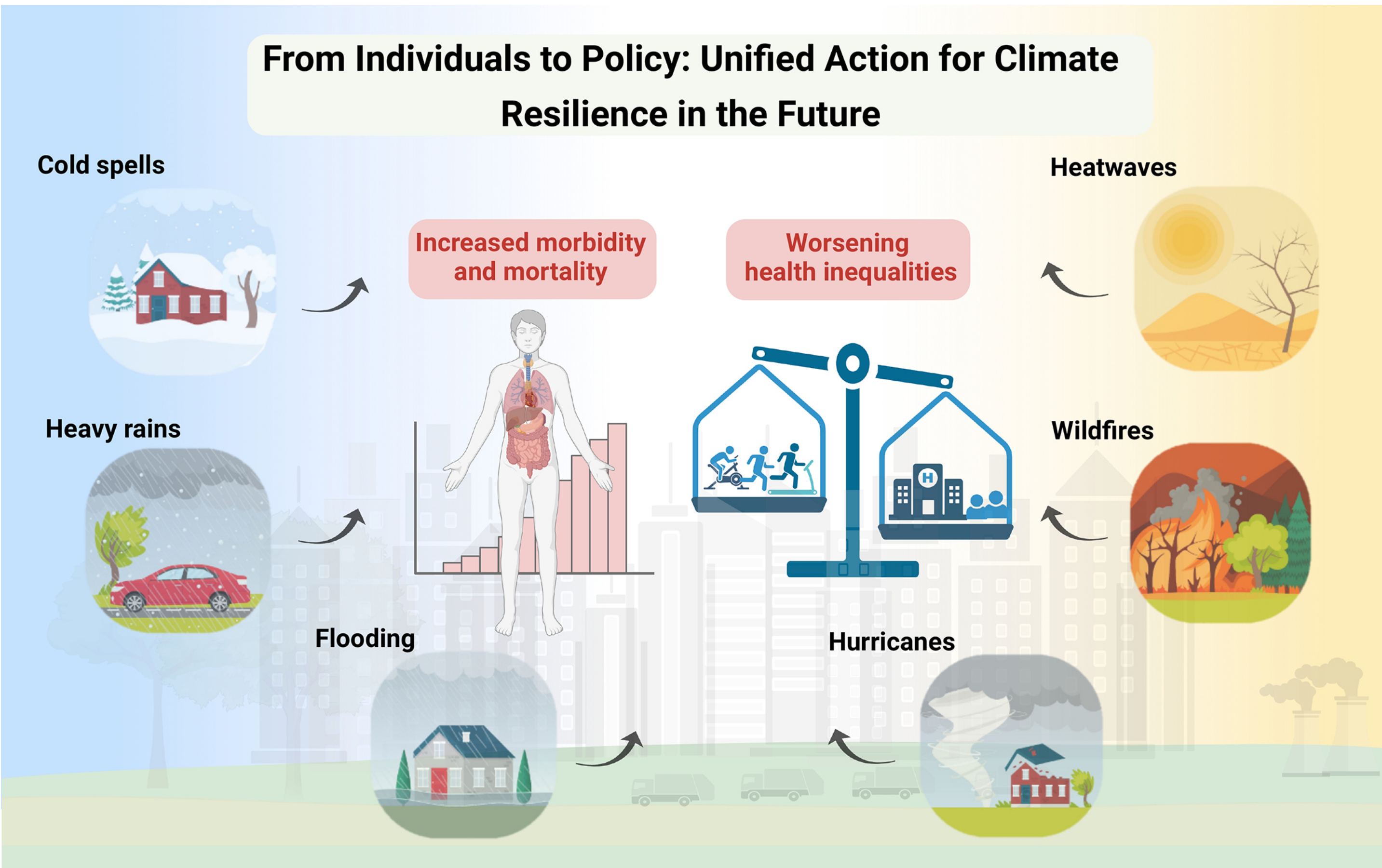
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Climate change is increasing environmental extremes, posing growing risks to human health.
- Extreme weather affects health in many ways; heart, lung and mental illnesses are well-studied examples.
- Health adaptation to climate extremes works best when actions from individuals to public policy are connected.
- Future research should guide fair adaptation and build climate resilient health systems.

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In the context of climate change, extreme environmental events are becoming increasingly frequent and severe, profoundly affecting human health and creating a vicious cycle of mutual reinforcement. This review examines evolving trends in climate change–related extreme events and compound exposures, such as heatwaves, cold spells, heavy rainfall, floods, and hurricanes, and summarizes their impacts on major health outcomes, including respiratory, cardiovascular, cerebrovascular, infectious, and kidney diseases, as well as mental health and adverse birth outcomes. It further outlines interventions and future directions for adaptation, planning, and resilience across six levels: individual, interpersonal, community, institutional, environmental, and public policy. Despite growing research in this area, substantial knowledge gaps remain, including the scarcity of evidence from low- and middle-income countries, methodological inconsistencies, limited investigation of compound events, and insufficient attention to morbidity and adaptation effectiveness. Future research should employ harmonized, long-term, and multi-regional approaches to more accurately quantify health burdens and enhance global resilience to climate change.

INTRODUCTION

Climate change has evolved from a distant concern into an urgent global health crisis. The Intergovernmental Panel on Climate Change (IPCC) reports that human-induced warming is already driving widespread alterations in weather and climate extremes across all regions, with heatwaves, heavy precipitation, droughts, and storms becoming increasingly frequent and severe.[1] The World Health Organization (WHO) emphasizes that these intensifying extreme events serve as a "threat multiplier," eroding decades of progress in public health by disrupting ecosystems, infrastructure, and social systems.[2]

The *2024 Lancet Countdown* reports a 167% increase in heat-related mortality among adults aged ≥65 years compared with the 1990s baseline, 102 percentage points above non-warming scenarios.[3] From 1961–90 to 2014–23, 61% of global land area experienced more extreme precipitation days, and 48% faced at least one month of extreme drought in 2023, the second-largest extent since 1951.[3] Beyond heat and floods, wildfires have emerged as another major and escalating climate-related health hazard. Globally, an estimated 0.22 million respiratory deaths annually between 2000 and 2019 were attributable to wildfire smoke, with an average 1.67% increase per year.[4] Average annual weather-related losses rose by 23% from 2010–14 to 2019–23, reaching USD 227 billion—greater than the GDP of roughly 60% of global economies.[3]

The health consequences of these extreme events are multifaceted. Acute exposures to heatwaves and cold spells elevate the risks of cardiovascular, cerebrovascular, and respiratory diseases, while floods and hurricanes increase the incidence of infectious disease outbreaks and waterborne illnesses.[5] Repeated or prolonged exposures further contribute to chronic diseases, mental health disorders, and psychosocial stress.[1,2,6] In addition, multiple climate extremes can occur simultaneously or sequentially, the compound events, thereby amplifying adverse health effects through nonlinear and synergistic pathways.[7]

Given these challenges, a comprehensive understanding of the evolving relationships among climate change, extreme environmental events, and human health is urgently required. This review aims to (1) characterize the temporal and spatial patterns of climate change–related extreme and compound events; (2) synthesize current evidence linking these exposures to key health outcomes, including respiratory, cardiovascular, cerebrovascular, infectious, renal, mental, and perinatal health; and (3) outline adaptation and resilience strategies across six interconnected levels: individual, interpersonal, community, institutional, environmental, and policy. By identifying critical knowledge gaps and future research priorities, this review seeks to inform coordinated global efforts to enhance health resilience in the face of climate change.

Extreme weather events influenced by climate change

Climate change is increasing the frequency, intensity, and duration of extreme weather events worldwide, including heatwaves, cold spells, heavy rainfall and floods, droughts, tropical cyclones, and wildfires (Figure 1). In this section, we summarize the trends, mechanisms, and health outcomes associated with each type of climate-driven extreme event.

Heatwaves and cold spells. Heatwaves are generally described as periods of unusually high temperatures, typically relative to local temperature percentiles and lasting from several days to months.[8] The 2010 Russian heatwave caused over 50,000 deaths,[9] while similar events in Europe (2003), Asia (2015), and Australia (2019-2020) likewise inflicted severe health burdens and economic losses.[10-12] Driven largely by anthropogenic greenhouse gas forcing,[13,14] the rising global heatwaves are further amplified by land-atmosphere feedbacks and regional factors such as urbanization and aerosols.[14-16] Historical global warming has increased both the severity and

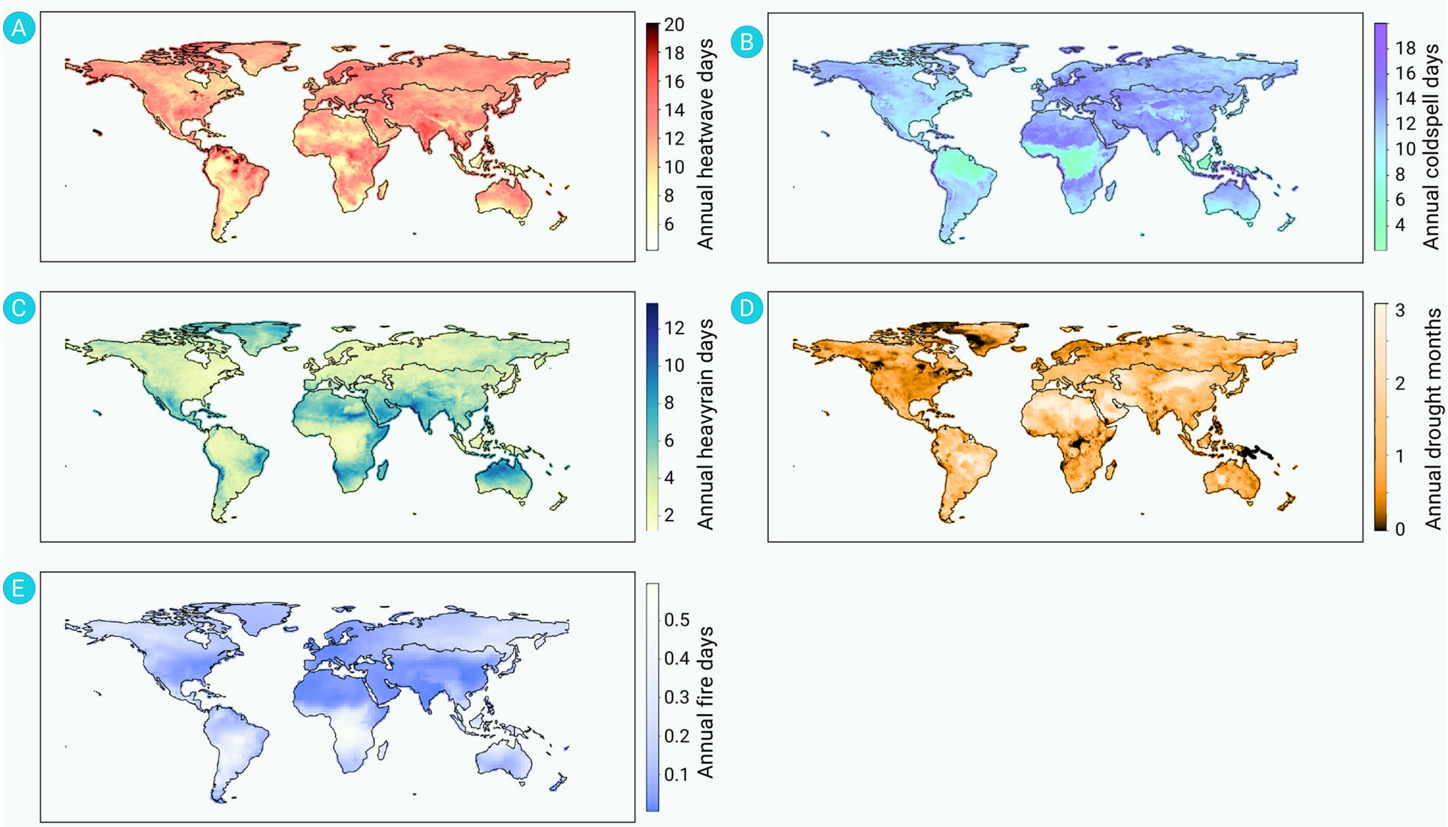

Figure 1. Annual days of heat waves, cold spells, heavy rains, droughts, wildfires.

likelihood of the hottest monthly and daily temperature extremes across most regions of the world.[17] The number of record-breaking monthly temperature events is five times higher than what would be expected without climate change.[18] Climate model simulations suggest that heatwaves will become more frequent, prolonged, and intense as temperatures continue to rise. Even under low to moderate-emission scenarios, mid-latitude regions could experience more than 60 days per year of potentially lethal heat by the end of the century.[19]

Cold spells, in contrast, generally refer to periods of extremely low temperatures lasting several days.[20] Although they occur more frequently than heatwaves in many regions,[21,22] the overall frequency and intensity of cold spells have declined globally since 1950, a trend also linked to anthropogenic greenhouse gas forcing.[14] Although anthropogenic warming reduced the frequency of the 2023 China cold wave by approximately 92%,[23] regional trends remain heterogeneous.[24,25] The average frequency of cold spells in Korea and Japan increased by over 50% in the 2010s compared to the 1990s.[24] Similarly, despite 2023 being the warmest year in decades, Northern Europe experienced an extreme cold spell in November,[26] potentially linked to expanded early-winter Arctic snow cover.[25,26] While the overall frequency and intensity of cold spells are projected to decline globally under continued warming, the associated health and economic burdens may increase due to population ageing and growing societal vulnerability.[14,27]

Heavy rains, hurricanes and floods. Heavy rains defined as intense precipitation events that greatly exceed normal levels within a short period.[28] Such conditions are conducive to triggering flash floods, disrupting infrastructure, and causing extensive water accumulation. In recent decades, both the frequency and intensity of heavy rains have increased on daily, hourly[29] and even sub-hourly scale.[30] Near Sydney, Australia, sub-hourly extreme rainfall has intensified at a statistically significant rate of at least 20% per decade over the past 20 years, based on weather radar and gauge observations.[30] This trend is linked to a warming climate that elevates evaporation rates and the atmosphere's moisture-holding capacity, thus increasing the volume of water vapor available for precipitation in brief periods.[30] Continued warming is likely to further intensify heavy precipitation, increasing the frequency and severity of short-duration rainfall extremes in many regions.[31]

Hurricanes are powerful tropical cyclones with sustained winds exceeding 74 miles per hour, often accompanied by torrential rains and storm surges.[32] These storms originate over warm ocean waters and can cause widespread destruction upon making landfall. In recent years, hurricanes have shown an upward trend, fueled by warmer ocean temperatures that provide more energy for these powerful storms.[33] Globally, the population exposed to hurricanes has been increasing year by year.[34]

Floods occur when water overflows beyond its usual limits, spilling over land areas.[35] They can result from prolonged rainfall, rapid melting of snow, or obstructions in drainage systems and rivers. Instances and severity of flooding have increased globally, influenced by more frequent heavy rain events, quicker snowmelt due to warmer air temperatures, and rising sea levels that hinder the natural drainage of floodwaters.[36] Climate warming is expected to heighten pluvial flood hazards by intensifying heavy precipitation, with the most significant increases occurring in regions characterized by greater water availability.[31,36]

Wildfires. Wildfires are an increasingly prominent climate change-related environmental extreme, driven by rising temperatures, prolonged drought, altered precipitation patterns, and land-use change.[37,38] Climate warming reduces fuel moisture, increases the number of hot, dry, and windy days, and prolongs seasonal drought, resulting in progressively drier and more flammable vegetation and the accumulation of combustible fuels.[39] These processes lengthen fire seasons and increase days with extreme fire weather.[40] Climate-driven shifts in vegetation structure and ecosystem composition interact with existing fire regimes, population growth, and land-use expansion to further alter fire behaviour.[41] The effects are strongly regional: although burned area has declined in some regions due to land-use change and agricultural expansion, rapid expansion of the wildland-urban interface and long-standing fire-suppression policies that encourage fuel build-up have increased human exposure to wildfire hazards and the scale of potential disasters.[42,43] As climate change continues to intensify fire-prone conditions globally, wildfires are expected to play an increasingly important role in shaping climate-related disease burdens.

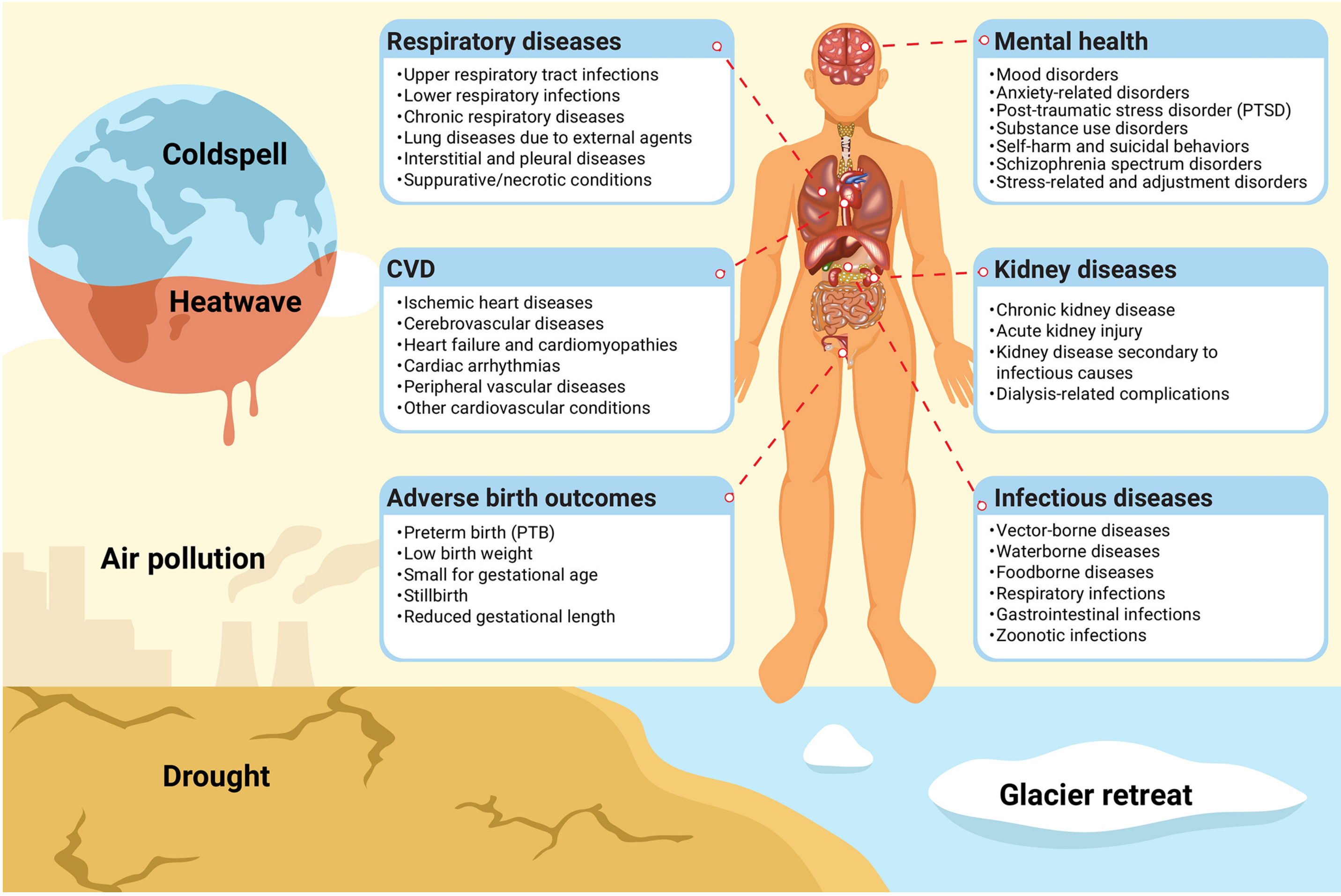

Figure 2. Overview of health outcomes impacted by climate change related environmental extremes.

Compound events. The compound event, defined as "a combination of multiple drivers and/or hazards that contributes to societal or environmental risk", was first introduced in the IPCC report and later integrated within its risk framework.[44] As such events can greatly amplify damage and risks to human health and the environment, research on compound events has grown rapidly.[45,46] Compound events often arise from shared meteorological conditions, temporal concurrence, and spatial coherence, frequently linking multiple extreme weather events.[47] For instance, the strong negative correlation between temperature and precipitation always results in compound dry-hot extremes (CDHE) during warm seasons.[48] The simultaneous or consecutive occurrence of storm surges and extreme rainfall caused by tropical cyclones can lead to compound flooding.[49] Moreover, compound events existed between extreme weather and air pollution. Prolonged extreme drought and extreme heat exposure will increase wildfire risks and cause severe air pollution.[50] The stagnant high-pressure systems, high temperature, and droughts were closely linked to peak ozone levels, which would increase by 10%-80% during heatwave.[51,52] Severe $PM_{2.5}$ pollution were predominantly observed in winter, and the pollution levels could resurge and intensify with a cold surge event.[53,54]

In recent decades, the climate change has altered meteorological conditions, intensifying compound events. From 1949 to 2016, global warming slowed tropical cyclone translation and increased atmospheric moisture, amplifying precipitation and flood risks.[55] Simultaneously, CDHE rose globally, particularly in western United States, southern India, and northeastern China,[56] extending fire seasons by 19% and doubling burned areas.[57] From 1995 to 2014, there were 2.6 days and 3.8 million person-days per year of heatwave and ozone pollution compound event worldwide, on average.[58] Despite rising temperature, the total event days of cold spell and $PM_{2.5}$ pollution events increased in eastern Asia.[59] As climate change prolonged, the impact of compound events will amplify continuously. Due to the increase in heatwaves, the occurrence of CDHE is projected to trend upward across all emission scenarios, with recurrence intervals decreasing from 2-4 years to below 1.5 years.[60] For heatwave and ozone pollution compound events, the total event days and exposure person-days were projected to increase to 13 times and 24 times the baseline levels (1995-2014) by 2071-2090 under the SSP3-7.0 (high-emission scenario).[59] Furthermore, a 1.5°C warming is projected to double the frequency of tropical cyclone-heat events over a 30-year period compared to the baseline level (1981-2010).[61]

In summary, the challenge posed by compound events arising from climate change remains critical, underscoring the urgent need for effectively response measures and adaptation policies to tackle this issue.

Extreme weather events and major health outcomes

Extreme weather events exert wide-ranging effects on human health through both direct and indirect pathways.[5] These exposures can cause acute physiological stress, injuries, and healthcare disruptions. They may also lead to longer-term health consequences through downstream effects such as air pollution, water contamination, food insecurity, and psychosocial distress.[5] Robust evidence links them to respiratory and cardiovascular diseases, infectious diseases, mental health disorders, kidney injury, and adverse birth outcomes (Figure 2). Collectively, these findings underscore the systemic nature of climate-related stressors and the urgent need for integrated prevention and adaptation strategies.

Respiratory diseases. Respiratory diseases are major climate-sensitive illnesses, influenced by both direct and indirect effects of extreme weather events.[62] Heatwaves, cold spellss, heavy rainfall, droughts, and wildfires can impair lung function and exacerbate pre-existing respiratory conditions. These exposures may also increase the risk of developing asthma, chronic obstructive pulmonary disease (COPD), and lung cancer.[63-65] Patients with pre-existing impaired lung function are particularly vulnerable to extreme climate conditions and face heightened risks of disease exacerbation and death. Heat significantly impacts respiratory health. For instance, a recent study estimated that heat-attributable respiratory mortality in Japan was 0.79 (95% empirical confidence interval [eCI]: 0, 1.50) deaths per 100 000 population in the 2010s under the SSP5-8.5 scenario. This value is projected to rise to 1.39 (95% eCI: 0.09, 3.44) in the 2050s and 2.79 (95% eCI: –0.12, 7.27) in the 2090s.[66]

Emerging evidence from epidemiological studies indicates a compelling association between rainfall events and adverse health outcomes for respiratory system. For example, the number of annual average excess deaths related to extreme precipitation events during 1986–2005 was 181 (95% CI: 79, 279) for respiratory disease in China, and are projected to increase by 78 (95% CI: 34, 120; approximately 43%) deaths in the 2030s, but decrease by 27 (95% CI: 12, 42) deaths in the 2090s under the low-fertility-rate population scenario (SSP2-S1).[67] Moreover, a long-term time-series analysis across 173 US counties showed the risk of respiratory diseases affected by air pollution.[68] The risk of respiratory hospitalisation increased by 0.34% (95% posterior credible interval [PCI]: 0.12%, 0.55%) per 10 μg/m^3 increase in previous day $PM_{2.5}$. The mortality from respiratory diseases caused by ozone and $PM_{2.5}$ demonstrated a notable increase across various future scenarios. Globally, Fang *et al* [69] projected 5% of increasing respiratory disease mortality attributable to ozone in 2100. Another Chinese study projected that the respiratory disease mortality attributable to $PM_{2.5}$ will increase up to 4.5% under SSP4 in 2030.[70] Drought and wildfire have also been proven to increase the mortality risk caused by respiratory diseases. The risk increases by 1.55% (95% PCI: 0.17%, 2.95%) compared to non-drought periods during the period of high-severity worsening drought.[71] During and after wildfires, the risks of respiratory morbidity increased by 33% (relative risk: RR) (95% CI: 10%, 59%) and 55% (95% CI: 42%, 69%), respectively, for each 10 μg/m^3 rise in $PM_{2.5}$ levels relative to pre-wildfire conditions.[72] Future projections for drought and wildfire impacts remain limited. The occurrence of extreme weather events often triggers compound phenomena, thereby amplifying health risks. A study indicated that extreme temperatures combined with COVID-19 led to 19 (95% CI: 16, 22 in North West England) to 24 (95% CI: 20, 29 in Wales) excess deaths per 100,000 population during heatwaves and 80 (95% CI: 75, 86 in Yorkshire and the Humber) to 127 (95% CI: 123, 132 in East of England) excess deaths per 100,000 population during cold spells, which were at least double higher than those from the previous decade.[73] A latest study finds that compared with the baseline of 1995–2014, by 2071–2090 under the high-emission scenario of SSP3-7.0, an increased annual mean of 34.6 compound-event days and mean population-exposure of 93.5 million person-days are expected.[59] Consequently, the rise of compound events necessitates growing public awareness and implementation of strategic interventions owing to increasingly severe threats to respiratory health.

Cardiovascular diseases. Cardiovascular disease (CVD) is the leading global cause of death with approximately 19.1 million deaths in 2020 (age-adjusted death rate: 239.8 per 100,000 population).[74] Climate change exacerbates CVD risk through various environmental exposures, including extreme weather events, fluctuating temperatures, and increased air pollution,[75–76] with high temperatures being the most studied pathway.[77–78]

High temperatures have been linked to increased cardiovascular mortality and morbidity. One study from England and Wales found that a 1°C rise above regional thresholds raised summer cardiovascular mortality by 1.8%.[79] In Kuwait, one of the hottest countries globally, extreme temperatures at the 99th percentile (42.7°C) nearly tripled cardiovascular mortality.[80] A global study across 32 countries found that heat-related deaths accounted for 0.66% (95% CI: 0.49%-0.98%) of all cardiovascular deaths.[81] Another study of 27 countries demonstrated associations between hot temperatures and elevated risks of ischemic heart disease, stroke, heart failure, and arrhythmia, potentially accounting for 2 deaths per 1,000 cardiovascular deaths.[82] Heatwaves further amplify risks. One meta-analysis found that heatwaves of at least 35°C for three days elevated cardiovascular mortality risk by 21%, while milder heatwaves led to a 9% increase.[83]

Cold temperatures also heighten CVD risk. One study from the Euro Winter Group reported that each 1°C temperature drop is linked with increased mortality from ischemic heart disease and cerebrovascular events in Europe.[84] In China, extreme cold (below the 2.5th percentile, −1.4°C) increased cardiovascular mortality by 92%, with effects persisting for over two weeks.[85] Globally, cold-attributed cardiovascular deaths may reach 8.2%.[81]

Air pollution, especially particulate matter ($PM_{2.5}$ and PM_{10}) and ozone, compounds these risks. Long-term exposure to $PM_{2.5}$ in the US was associated with a 10% increase in cardiovascular mortality for every 10 μg/m^3 increase.[86] Short-term $PM_{2.5}$ exposure is associated with increased myocardial infarction (MI) incidence,[87] and long-term exposure significantly raises MI risk.[88] For heart failure, a 10 μg/m^3 increase in $PM_{2.5}$ corresponded to a 2.12% rise in hospitalizations.[89] One UK Biobank study revealed a 31% higher heart failure incidence among individuals in the highest pollution quartile.[90] Studies on stroke have shown that a 10 μg/m^3 $PM_{2.5}$ rise increases stroke incidence by 13% and cerebrovascular mortality by 24%.[88]

There is increasing attention on the combined adverse effects of air pollution and temperature on CVD health. A study across eight European cities found that the effects of particulate matter on cardiovascular mortality were heightened on hotter days, with ozone-related mortality also rising with temperature.[91] This combined impact likely results from synergistic strain such as increased blood viscosity and oxidative stress. A recent systematic review by Anenberg et al.[92] supports a dose-response relationship, showing significant combined impacts on cardiovascular mortality. Furthermore, a study in California demonstrated that co-exposure to extreme heat and $PM_{2.5}$ raised cardiovascular mortality rates above individual exposures.[93] Another study analyzed cardiovascular mortality across 482 locations in 24 countries from 2000 to 2018, focusing on heat effects and their modification by air pollution levels during warm months: the results showed that cardiovascular mortality increased by 1.6%, 5.1%, and 8.7% at low, medium, and high levels of O_3, respectively.[94] These findings suggest that climate change-related compounded pollution effects may exceed independent projections.

Indirectly, climate change impacts cardiovascular health by complex exposure pathways, including disrupting access to healthy food, clean water, transportation, housing, electricity, communication systems, medical assistance, and other social determinants of health.[75]

Infectious diseases. Extreme weather events driven by climate change impact infectious disease dynamics by altering ecosystems to favour the survival, growth, and transmission of pathogens. Extreme temperatures, including heatwaves and cold spells, significantly impact infectious disease transmission. Heatwaves create optimal conditions for vector-, foodborne-, and waterborne- diseases by accelerating vector reproduction and pathogen growth.[95–99] A systematic review concluded that increased temperatures significantly impact infections from five major food-borne pathogens: Salmonella, Shigella, Campylobacter, Vibrio, and Listeria.[99] Another meta-analysis reported a 13% increase in dengue infection risk per 1°C rise,[100] with similar findings in other studies.[101-105] Other associations have been observed with malaria, Japanese encephalitis, West Nile virus, cholera, salmonellosis, shigellosis, and viral gastroenteritis. [95–96,99,104,106] Cold spells are also associated with respiratory infections like influenza and RSV, with low temperatures boosting viral stability, particularly in temperate regions.[107–108] Generally, the impact of extreme temperatures on infectious diseases often exhibit delays, ranging from 1–2 weeks for influenza, 3–6 weeks for diarrhoea, 7–12 weeks for malaria and 6–16 weeks for dengue fever,[109] highlighting the need for early warning systems.

Heavy rainfall, hurricanes, and floods are also significantly linked to infectious disease outbreaks, especially waterborne illnesses, via sewer overflows and water contamination.[110–111] A meta-analysis showed a 40% rise in post-flood diarrhea incidence, particularly for bacterial and parasitic cases.[112] Flooding also significantly impacts cholera, leptospirosis, hepatitis A, and respiratory infections.[110–111,113–114] Hurricanes and cyclones, while varying in impact by disease type, generally increase infectious disease cases and hospitalisations,[115–116] with immediate rises in intestinal and contact-transmitted infections[117] and elevated risks of leptospirosis, dengue, and infectious diarrhea for up to four weeks after events.[118-120] Conversely, respiratory infections, measles, mumps, varicella, and vivax malaria may show decreased risks.[117–118,120] Hurricanes and cyclones further elevate disease spread by disrupting sanitation and overcrowding shelters, with prolonged risks for up to a year.[98,121]

The increasing prevalence of compound events significantly increases infectious disease risk.[122] Heatwaves paired with droughts exacerbate water scarcity, pollution, and hygiene issues, increasing outbreak risks,[123–124] while hurricanes and floods together heighten gastrointestinal infections due to widespread water contamination.[125] In cold regions, cold spells combined with high particulate matter significantly raise respiratory risks.[107] A study across 168 Chinese cities found that pollutants worsened cold-induced pneumonia hospitalizations due to lower air dispersion.[108] These interactions highlight the challenges of compound events in preventing infectious diseases. With climate change expected to increase the frequency and intensity of such events, global disease transmission risks and burdens are projected to rise.

Mental and neurological health. Mental health can be severely affected by extreme weather events, from direct trauma, such as injury or displacement, and indirect stressors, including loss of livelihood, healthcare disruption, and ongoing uncertainty.[126-128] Among them, heatwaves have been consistently linked to elevated psychiatric risks. A case-crossover study across 2775 U.S. counties (2010-2019) found that extreme heat days (≥95th percentile) were associated with a 8% increase in emergency department (ED) visits for any mental health condition (IRR 1.08; 95% CI: 1.07, 1.09), particularly for substance use disorders, anxiety-related conditions, mood disorders, self-harm, and schizophrenia-spectrum disorders.[129] Cold spells have also been linked to poorer mental health. A study of over 8,000 individuals found that warmer temperatures during cold seasons were associated with significantly lower perceived stress (β = -0.15 to -0.24) and better self-reported health (β = 0.18).[130] Hydro-meteorological hazards including heavy rainfall and flooding often induce both immediate and long-term psychological distress. A population-based study in the UK showed that people displaced by flooding had nearly double the odds of probable depression (OR=1.95, 95% CI: 1.30, 2.93), anxiety (OR=1.66, 95% CI: 1.12, 2.46), and PTSD (OR=1.70, 95% CI: 1.17, 2.48) one year after the event compared to those flooded but not displaced.[131] Tropical cyclones and hurricanes have been repeatedly linked to severe mental health consequences. In the aftermath of Hurricane Ike, which devastated parts of the Texas coast in 2008, structured interviews with 255 affected adults showed that 5.9% met criteria for PTSD, 4.5% had major depressive episodes, and 9.3% reported generalized anxiety disorder.[132]

Compound extreme events pose unique and escalating risks to mental health. Unlike isolated events, compound extremes often amplify the intensity, duration, and geographic spread of stressors, increasing psychological toll through layered traumas, prolonged recovery, and cascading social disruptions.[133-135] For instance, after Hurricane Sandy in New York City and Long Island, self-reported home flooding was significantly associated with elevated risks of anxiety (OR: 1.50; 95% CI: 1.10, 2.04), depression (OR: 1.69; 95% CI: 1.26, 2.26), and PTSD (OR: 2.53; 95% CI: 1.78, 3.59).[136] Other compound events such as extreme heat combined with wildfires have been shown to increase mental distress due to both direct threats and poor air quality.[137] Similarly, the concurrence of cold spells with high particulate matter levels exacerbates psychological symptoms, particularly in urban populations exposed to pollution.[138] Drought combined with extreme heat further intensifies stress, especially among agricultural communities facing economic hardship.[139] These overlapping exposures create complex challenges for mental health services, highlighting the need for integrated climate and health interventions.

As climate change accelerates, extreme weather events are projected to exacerbate mental health risks worldwide.[140-142] More frequent heatwaves, prolonged droughts, and intensifying storms bring a chronic climate stress, disproportionately affecting low-resource and high-risk communities.[143] Psychological impacts may no longer be limited to post-disaster phases but could become chronic and anticipatory, manifesting as climate anxiety, or a pervasive sense of loss and uncertainty about the future.[144] Youth and Indigenous communities may be particularly vulnerable due to their cultural ties to land and future-oriented concerns.[145–146] Climate-related displacement, resource scarcity, and social fragmentation further compound these stressors, potentially undermining mental health systems' capacity to respond.[147]

Beyond mental health, climate-related environmental extremes also compromise neurological health. Extreme heat threatens older adults and people living with neurodegenerative disease by exacerbating thermoregulatory failure, neuroinflammation, cerebrovascular strain, and dehydration, thereby precipitating acute neurological injury or deterioration of chronic conditions. In a nationwide U.S. study of Medicare beneficiaries with Alzheimer's disease and related dementias (ADRD), four consecutive days of extreme heat (≥99th percentile heat index) increased ADRD-related hospitalisations by 4% (OR 1.04; 95 percent CI 1.03, 1.04), with stronger effects among socially disadvantaged groups.[148] Similar associations between temperature variability and neurological admissions have been reported in multiple settings, via systemic inflammation and cerebrovascular dysfunction.[149] Wildfire smoke may also affect brain health. Experimental and epidemiological studies link smoke-derived fine particles with neuroinflammation, oxidative stress, and cerebrovascular injury, and emerging human research suggests possible increases in cognitive decline, dementia exacerbations, stroke, and seizure risk.[150] Such risks may be magnified during concurrent heat and wildfire events, disproportionately affecting older adults and individuals with pre-existing neurological disease. Consequently, the brain should be recognised as a potential target organ of climate-related environmental extremes. Priority research needs include longitudinal assessment of extreme exposures, compound events, and equity-focused analyses of susceptible groups.[151]

Kidney diseases. Kidney disease poses a major public health problem with the global median prevalence of chronic kidney disease (CKD) reaching 9.5% (IQR: 5.9%, 11.7%).[152] It was estimated that people with kidney disease exceeded 850 million worldwide.[153] Under the context of global warming, the kidney is one of the main organs to protect human body for heat and dehydration, also the first to be damaged. The pressure on kidney is intensified by ongoing global warming and frequent environmental extremes.

A review in 2021 reported an increase of 1% (95%CI: 0.9%, 1.1%) in kidney-related morbidity and 3% (95%CI: 1.8%, 4.5%) in kidney-related mortality per 1°C increase in temperature.[154] The study in 261 major Chinese cities showed that for a 1°C increment in daily mean temperature, the RRs were 1.008 (95%CI: 1.003, 1.012) of hospitalizations for CKD. And compared with non-heatwave days, heatwaves exposure was associated with 11.6% (95%CI: 6.9%, 16.6%) increased risks of hospitalizations for CKD.[155] The study in Queensland, Australia reported that the risk of heat-related hospitalization for acute kidney injury (AKI) increased from 1.22 (95% CI: 1.10, 1.35) in 1995 to 1.67 (95% CI: 1.57, 1.77) in 2016, suggesting the accelerating influence of global warming.[156] Occupational cohort studies in Central America confirm that strenuous work in extreme heat without adequate rest or hydration drives the epidemic of chronic kidney disease of nontraditional causes (CKDnT).[157-159]

Cold exposure also elevates risks. A Korean study reported that low temperatures and cold spells were associated with increased AKI hospital admission risks, with estimates of 1.12 (95% CI: 1.09, 1.16) and 1.87 (95% CI: 1.46, 2.39), respectively.[160] The national study in China showed that extreme cold exposure was associated with increased risks for kidney disease mortality (OR=1.34; 95%CI: 1.27, 1.41). Projections in this study implied that heat-related attributable fractions (AFs) of kidney disease mortality would increase from 2.82 % (95 %CI: 1.8 %, 4.20 %) in the 2050s to 7.12 % (95 %CI: 4.23 %, 10.09 %) in 2090s under SSP5-8.5, while the decrease of cold-related AFs from 8.57 % (95 %CI: 5.71 %, 9.89 %) to 8.14 % (95 %CI: 5.22 %, 8.81 %) can barely offset the increased burden.[161]

Epidemiological evidence is limited on associations between heavy rains or floods and kidney disease. Floods can lead to the contamination of water supplies, increasing the risks for diarrheal and rodent-borne diseases.[162] These infectious diseases are recognized as driving causes of AKI.[163] Moreover, damage to critical infrastructures such as transportation or the closure of dialysis centers may prevent dialysis patients from seeking dialysis supplies.[164] Wildfire impacts kidney function mainly through smoke emission and related air pollution. One study in US found increased CKD mortality risks at specific wildfire smoke $PM_{2.5}$ thresholds.[165]

Both long-term and short-term air pollution exposures significantly drive kidney disease. A review in 2023 showed that pooled estimated ORs of risk for CKD were 1.42 (95%CI: 1.31, 1.54) per 10 μg/m^3 increase in $PM_{2.5}$; 1.20 (95% CI: 1.14, 1.26) per 10 μg/m^3 increase in PM_{10}; 1.07 (95%CI: 1.05, 1.09) per 10 μg/m^3 increase in NO_2; 1.03 (95% CI: 1.02, 1.03) per 10 μg/m^3 increase in NO_X; 1.07 (95%CI: 1.01, 1.12) per 1 ppb increase in SO_2; 1.03 (95% CI: 1.00, 1.05) per 0.1 ppm increase in CO, respectively.[166] The study involving six countries/territories reported that the RRs for AKI-related deaths were 1.052

(95%CI: 1.003, 1.103) per 5 μg/m^3 increment in $PM_{2.5}$ and 1.022 (95%CI: 0.994, 1.050) per 10 μg/m^3 in O_3 and 1.022 (95%CI: 0.982, 1.063) per 10 μg/m^3 in NO_2.[167]

Compound exposures to environmental extremes may amplify kidney disease risks compared with individual exposures. For example, a multiplicative interaction effect of 1.052 (95% CI: 1.019, 1.087) between outdoor temperature at the 99th percentile and $PM_{2.5}$ exposure was observed for AKI in a case study conducted in New York.[168] Wu et al. also found that the association between NO_2 exposure and CKD-related hospital visits was more pronounced during low temperatures.[169]

Adverse birth outcomes. Adverse birth outcomes are associated with increasing both morbidity and mortality risks among children under five years of age.[170-172] Accumulating epidemiological evidence suggests that prenatal or preconception exposure to extreme weather events can influence birth outcomes through various direct and indirect pathways.[173–174] Extreme weather events may act as direct environmental stressors contributing to adverse birth outcomes. They may also exert indirect effects through alterations in the physical environment (e.g., increased air pollution, food and water scarcity, or shifts in pathogen distribution) and the social environment (e.g., displacement, resource-related conflicts, and food insecurity). These exposures can induce biological and physiological disturbances such as oxidative stress, inflammation, malnutrition, and infection, as well as psychological stress, all of which collectively increase the risk of adverse birth outcomes.[173–174]

Common adverse birth outcomes, including preterm birth (PTB), low birth weight (LBW), small for gestational age (SGA) and stillbirth, have frequently been reported to be linked with extreme weather events. A meta-analysis found that prenatal exposure to heatwaves (temperatures ≥ 90th percentile) increased the risk of PTB, LBW and stillbirth, with ORs of 1.60 (95% CI: 1.10, 1.23), 1.14 (95% CI: 1.11, 1.16) and 1.46 (95% CI: 1.09, 1.96), respectively.[175] Stillbirth risk was highest with exposure during the first trimester,[176] while exposure to heatwaves (> 95th percentile) during the third trimester significantly increased the SGA risk (OR: 1.17; 95% CI: 1.13, 1.22).[177] Similarly, exposure to low ambient temperatures during the third trimester increased the risks of PTB (RR: 1.16; 95% CI: 1.12, 1.20) and LBW (RR: 1.22; 95% CI: 1.11, 1.33) but not stillbirth (RR: 1.53; 95% CI: 0.98, 1.12) or SGA (RR: 1.01; 95% CI: 0.92, 1.12).[178] Owing to the period of pregnancy (< 10 months), studies exploring the combined effects of prenatal exposure to both high and low temperatures on adverse birth outcomes remain scarce.

The frequency and intensity of other extreme weather events, such as excessive rainfall, hurricanes and floods, are expected to increase under ongoing climate change.[179–180] The majority of studies suggest that excessive rainfall and hurricanes are linked to an elevated risk of adverse birth outcomes. For instance, prenatal moderate exposure to extremely intense rainfall in Amazonia region was associated with a reduction in mean birth weight (60 g, 95% CI: 11, 110 g) and an increased risk of PTB, while high exposure led to a greater reduction in mean birth weight (183 g, 95% CI: 57, 319 g) and a markedly increased PTB risk (OR: 222, 95% CI: 16, 894).[174] A similar pattern was observed for an increased likelihood of LBW (2.52%, 10.34%) and PTB (5.20%, 13.53%), as well as a shortening of gestational length by 0.10 weeks (95% CI: 0.07, 0.14 weeks) following in utero exposure to hurricanes.[181] Moreover, there may be stronger effects of hurricane exposure during the first trimester or within two months before conception.[182] Additionally, exposed to both hurricanes and excessive rainfall resulted in a greater reduction in gestational length (0.11 weeks, 95% CI: 0.07, 0.16 weeks).[181]

However, evidence regarding the relationship between floods and birth outcomes remains inconsistent. A review indicated increased LBW and SGA prevalence rates after flood, though no significant difference was observed for PTB.[183] In contrast, another Pakistan study found no linkage between single flood exposure and adverse birth outcomes.[184] Interestingly, a cohort study in Australia found that flood exposure during the first trimester was related to an increased risk of PTB (HR: 1.03, 95% CI: 1.002, 1.05), stillbirth (HR: 1.11, 95% CI: 1.03, 1.20) and SGA (HR: 1.03, 95% CI: 1.01, 1.06), while exposure during 0-12 weeks before pregnancy or the third trimester was associated with reduced risks.[185] Considering the substantial physiological, metabolic, and endocrine changes occurring before and during pregnancy, together with the likelihood of multiple extreme weather exposures, disentangling specific effects of any single event on birth outcomes remains challenging.[186] Nevertheless, the adverse effects identified by previous studies highlight the urgent need for public health attention on extreme weather events.

Beyond their diverse clinical manifestations, climate-related extreme events also impose escalating economic pressures on health systems, by driving surges in healthcare demand and costs. For example, in Perth (Australia), non-optimal temperatures were estimated to account for approximately 4.6% of all emergency department presentations and several million Australian dollars in annual healthcare expenditure, with marked increases projected under high-emission scenarios.[187] In the United States, NOAA's Billion-Dollar Weather and Climate Disasters database records hundreds of weather- and climate-related events since 1980, each associated with losses of at least US$1 billion (inflation-adjusted) and collectively amounting to damages in the trillions.[188] During the 2019–2020 Black Summer fires in Australia, smoke-attributable health costs were estimated at AU$1.95 billion, more than nine-fold higher than the prior two-decade median.[189] In the United Kingdom, suboptimal temperature exposure has been estimated to account for around 3% of total healthcare expenditure.[190] Globally, the WHO estimates that direct climate-change-related health damages (excluding sectors such as agriculture, water, and sanitation) will reach US$2–4 billion annually by 2030.[191] These figures likely underestimate the true burden by omitting productivity losses, informal care, long-term disability, and many mental health outcomes. Collectively, these findings indicate that climate-related environmental extremes threaten not only population health but also the financial sustainability of health systems, reinforcing the need for integrated prevention, adaptation, and resilient health-system planning as core elements of climate policy.

Adaptation, planning and resilience for health

Adaptation, planning, and resilience strategies operate across multiple, interlinked levels to mitigate health risks associated with extreme weather events and climate change. These interventions span individual and interpersonal actions that reduce immediate exposure and vulnerability; community and institutional measures that coordinate preparedness and service delivery; and environmental and public policy interventions that shape the structural determinants of risk and protection. Collectively, these layers form an integrated adaptation continuum, in which actions at higher levels enable, reinforce, or constrain responses at lower levels. Understanding the interactions across these levels is essential for strengthening health resilience, reducing inequalities, and ensuring effective responses to increasingly frequent and severe climate-related hazards.

Individual and interpersonal interventions. Adaptation at the individual and interpersonal levels are often the first line of defence in protecting health beyond extreme weather events in the context of climate change.[192–193]

At the individual level, adaptation involves actions taken by a person to reduce their vulnerability to environmental exposures and adapt to associated health risks (Table 1). These are often focused on improving health literacy and personal behaviours, preparedness, and resource use, such as staying hydrated during heatwaves, creating evacuation plans, or stockpiling emergency supplies. Interpersonal interventions, on the other hand, refer to collaborative actions taken within close-knit groups, such as families, neighbourhoods, or friends. These strategies rely on personal relationships and direct interactions, such as sharing resources like water, food, or shelter with friends or family before and during the extreme weather events. For example, during extreme heat, individuals can stay hydrated and use umbrella or wear hat when going outside, while neighbours might assist vulnerable residents by ensuring access to cooling spaces. In the context of flooding, individuals may assemble emergency kits and stock necessary medicines, whereas family, friends, and neighbours could provide temporary housing.

These interventions are often the foundation of adaptation, especially in areas with limited institutional support or delayed government responses, as individual and interpersonal adaptions are flexible and can be tailored to the specific vulnerabilities, thereby addressing risks more effectively than general strategies. Interpersonal actions, particularly, can help reduce disparities by supporting marginalized or at-risk groups, as the stronger family or neigh-

Table 1. Selected examples of interventions in humans investigating personal and interpersonal strategies to reduce harms of extreme weather events.

Intervention	Implementation examples	Impacts of the intervention
Strategies to reduce exposure		
Air conditioning / fans	Use cooling devices during heatwaves	Reduces physiological heat stress and heat - related illness
Mask use	Wear protective masks during wildfire smoke or dust storms	Lowers inhalation of harmful air pollutants
Personal hydration	Increase water intake during extreme heat	Prevents dehydration and heat - related conditions
Family evacuation plans	Households rehearse evacuation procedures	Improves evacuation readiness and safety
Providing shade	Use umbrellas or temporary shading structures	Lowers direct solar and heat exposure
Protective clothing	Wear UV-blocking or weather-resistant clothing	Reduces exposure to heat, cold, and UV radiation
Strategies to mitigate the health impact of exposure		
Nutrition intervention	Maintain balanced diet during prolonged hazards	Supports general health during prolonged stress
Medication management	Maintain access to essential prescriptions	Prevents worsening of climate-sensitive chronic diseases
Information sharing	Exchange advice within families or neighbourhoods	Improves awareness and preparedness
Persuasive arguments	Encourage others to adopt safer behaviours	Increases uptake of protective actions
Mutual aid	Provide food, water, shelter to neighbours	Strengthens coping capacity when services are limited
Check-ins for vulnerable individuals	Regularly monitor elderly or disabled individuals	Enables early assistance during emergencies
Basic first-aid training	Learn first-aid skills within families or neighbourhoods	Improves immediate response to injury before medical care

bourhood networks with shared values enhance collective capacity to respond to and recover from extreme weather events.[194]

Despite their important role in climate risk adaptation, the individual and interpersonal interventions face several challenges that limit their effectiveness. First, structural and resource constraints remain a fundamental barrier, as individuals in low-income or remote areas and marginalized groups often lack access to resources, knowledge, and infrastructure despite increasing awareness of climate risks, substantially limiting their ability to respond effectively to extreme weather events. Second, societal and cultural norms can further impede adaptation efforts.[194–195] In some communities, social stigma or distrust discourage individuals from seeking or offering help, disproportionately affecting women. Traditional gender roles often place disproportionate caregiving responsibilities on women,[196] and restricted access to resources and decision-making authority can limit their climate risk awareness and adaptative actions. Third, psychological barriers also play a role.[195] Individuals without prior disaster experience may underestimate risks, while repeated exposure to extreme events can lead to "disaster fatigue", reducing motivation to prepare. Climate-related mental health, such as stress or trauma, further inhibit proactive adaptation, particularly among frequently affected populations.[197] Finally, urbanization and migration can erode traditional social networks that support adaptation. For instance, in Japan, the rural depopulation and repeated displacement caused by extreme weather events weaken community ties, undermining resource sharing and coordinated actions that are essential for resilience.[198]

Community and institutional interventions. Effective responses to climate extremes require multi-layered strategies from individual behaviors to governmental- and international-level actions, with community and institutional interventions playing a particularly critical role for building long-term resilience, ensuring equity, and protecting vulnerable populations.[199–200]

Community-level adaptation rests on five interconnected pillars, including infrastructure, community engagement, vulnerable-group identification, livelihood resilience, and risk communication, which collectively reinforce social cohesion, equitable protection, and sustainable preparedness (Table 2).

Infrastructure underpins community resilience by reducing physical exposure to hazards. Melbourne's Cooling Our City initiative, for example, combines large-scale tree planting (over 3,000 trees annually) with blue–green infrastructure to mitigate local urban heat by up to 4 °C.[201–202] Modeling studies further show that rooftop greening can lower air temperature by ~1.5 °C and improve thermal comfort by ~2.4 °C during summer heatwaves.[203]

Community engagement transforms capacity into coordinated action. The Cyclone Preparedness Programme (CPP) in Bangladesh mobilizes over 76,000 volunteers for early warnings and evacuation, dramatically reducing cyclone mortality since the 1990s.[204] In Australia, community-led bushfire programs such as Community Fireguard and Resilience NSW have strengthened local response capacities.[205]

Identification of disaster-prone communities and vulnerable groups enhances the precision and fairness of resource allocation. Many Japanese municipalities now use GIS-based flood hazard and vulnerability maps integrating rainfall, elevation, and demographic data to support evacuation and risk planning (e.g., Okazaki City).[206] GIS has thus become indispensable for evidence-based disaster management.[207]

Livelihood resilience fosters long-term adaptation through diversified income and insurance mechanisms. In India's Maharashtra state, the Project on Climate Resilient Agriculture (PoCRA) trains farmers in crop diversification and water-efficient practices, helping reduce drought-related income losses.[208–209]

Risk communication links information to action. Miami's Resilience Hub model integrates multilingual alerts, public education, and digital platforms to prepare diverse communities for hurricanes and floods, though access disparities persist.[210]

Institutional-level interventions complement community action through structured governance, technology, and workforce protection (Table 3). They center on four domains, including technological innovation, occupational health surveillance, institutional training, and cross-institutional cooperation each reinforcing systemic resilience.

Technological innovation provides both preventive and protective adaptation. Singapore's HeatSafe initiative employs wearable sensors and adaptive scheduling to protect outdoor workers under extreme heat, demonstrating measurable gains in heat-stress prevention.[211] In Spain, hospitals like Madrid's Severo Ochoa have adopted waste-heat recovery and energy-efficient cooling to maintain operations during heatwaves.[212]

Table 2. Community interventions examples that may reduce the health effects from exposure.

Intervention	Implementation examples	Impacts of the intervention
Infrastructure	- Expand access to temperature-controlled and hazard-resilient shelters (e.g., libraries, schools, emergency hubs). - Integrate blue–green infrastructure, such as green roofs, urban trees, and permeable surfaces.	- Reduce exposure to heat, flooding, and related environmental hazards. - Lower energy consumption while improving thermal comfort and resilience against climate extremes.
Community Engagement	- Facilitate participatory planning processes, including flood response drills and community consultations. - Establish early warning groups and volunteer networks to coordinate responses across climate extremes.	- Enhance community readiness, trust, and social cohesion. - Strengthen mutual support, collective action, and rapid emergency response capacity.
Vulnerable Groups Identification	- Prioritize support for populations sensitive to climate extremes (e.g., the elderly, children, people with disabilities, outdoor workers). - Use participatory mapping, census data, and GIS-based assessments to locate and assist at-risk households.	- Enable tailored interventions for sensitive groups under different hazard types. - Improve efficiency and equity in resource allocation during emergencies.
Livelihood Resilience	- Encourage diversification of livelihoods to reduce weather-related disruptions. - Provide insurance coverage for health, crops, and property losses caused by extreme events.	- Minimize economic losses and productivity disruptions during multi-hazard events. - Enhance recovery capacity and long-term community sustainability.
Risk Communication	- Conduct public awareness campaigns addressing risks from climate extremes. - Use multi-channel communication platforms (hotlines, social media, community apps) to disseminate emergency alerts. - Encourage neighbourhood-based communication and peer-to-peer knowledge sharing.	- Improve public understanding of multi-hazard risks. - Increase responsiveness to early warnings and foster informed decision-making. - Enhance long-term resilience through continuous education and information access.

Table 3. Institutional interventions examples that may reduce the health effects from exposure.

Intervention	Implementation examples	Impacts of the intervention
Introducing New Technology	- Deploy automation and remote operation technologies to minimize direct worker exposure to hazards such as heatwaves, storms, and air pollution. - Apply advanced protective materials including waterproof, fire-resistant, and thermal-regulating clothing. - Integrate energy-efficient and hazard-resilient building designs, such as hurricane-proof windows and improved thermal insulation.	- Reduce occupational exposure and enhance worker safety in hazardous environments. - Improve personal protection, lowering the risk of injury or illness linked to extreme weather conditions. - Strengthen the durability of infrastructure while reducing energy demand and operational disruptions.
Occupational Health Surveillance	- Conduct regular physical and psychological health assessments for employees in high-risk environments. - Use wearable devices to monitor temperature, humidity, and air quality in real time. - Maintain strict adherence to multi-hazard occupational safety standards and protocols.	- Enable early detection of hazard-related health issues and prompt preventive measures. - Provide timely alerts and responses to prevent heat stress, respiratory issues, or other environmental health impacts. - Reduce workplace injuries and fatalities by ensuring compliance with best practices.
Institutional Management & Training	- Modify work schedules to avoid exposure during periods of extreme weather, such as midday heat or heavy rainfall. - Deliver targeted staff training, including first-aid education, hazard awareness, and evacuation drills. - Provide and maintain appropriate personal protective equipment (PPE) for diverse hazard scenarios.	- Minimize health risks and fatigue by aligning work hours with safer environmental conditions. - Enhance staff readiness and improve the overall effectiveness of emergency responses. - Ensure continuous protection and resilience of the workforce under changing risk conditions.
Cross-Institutional Cooperation	- Establish robust legal frameworks, coordinated emergency protocols, and inter-agency governance systems. - Develop integrated early warning systems linking meteorological services, emergency responders, and public communication channels. - Promote data sharing, joint risk assessments, and adaptive planning for compound hazard scenarios.	- Improve institutional alignment and ensure unified responses to complex hazard events. - Facilitate rapid dissemination of critical information and enable proactive interventions. - Reduce economic losses and health impacts while building long-term socio-ecological resilience.

Occupational-health surveillance builds institutional foresight. During the 2022 FIFA World Cup, Qatar's Ministry of Labor implemented real-time heat-stress monitoring, flexible work-rest cycles, and shaded rest areas significantly reducing heat-related illness risk among construction workers.[213]

Institutional management and training strengthen preparedness through regular drills and education. In Japan, disaster simulations from school drills to coordinated municipal and hospital exercises are institutionalized nationwide to improve coordination and readiness.[214] Hospitals further incorporate advanced evacuation protocols emphasizing patient safety, communication, and energy continuity.[215]

Cross-institutional cooperation ensures cohesive responses to complex events. Latin American early-warning networks linking Mexico, Colombia, and Peru improve joint flood forecasting and post-disaster health management.[216] In Australia, Victoria's Heat Health Alert System (HARS) integrating meteorological, health, and emergency agencies, has improved public-warning timeliness and reduced heat-related mortality.[217]

Table 4. Environmental and public policy interventions examples that may reduce the health effects of exposure.

Intervention	Implementation examples	Impacts of the interventions
International climate policies	UNFCCC, Paris Agreement, Green Climate Fund	NDC ambitions, Climate Funds to support developing countries,
Greener cities	Green space, green infrastructures, urban nature-based recreations, low carbon cities, air pollution controls	Reduce air pollution and carbon emissions; increase physical activity; reduce mortality, mental health, respiratory diseases, cardiovascular risks, and loneliness
Heat Health Strategies	HHAPs, HHWS at governments at all levels	Mixed outcomes in HHAP evaluations; gaps in LMICs.
Sustainable transport	The Tehran Transportation Master Plan, "the TTMP" in the city of Tehran, Iran [244]	Decreased 12.9 million tons of CO_2 and 1.4 million tons of other pollutant emissions; prevented app. 10,000 deaths; more than USD 35 million savings by 2030.
	The bus rapid transit (BRT) in Hanoi, Vietnam [245]	Reduce 17%-23% emissions of air pollutants, up to 22.4 % carbon emission, and at least 4.8 % health risks.
	The mass rapid transit (MRT) system in Greater Kuala Lumpur, Malaysia [246]	Reduce 337,800 tons of CO_2e from private transport and 83 deaths and 9587 DALYs in population every year
Decarbonising health systems	UK NHS Net Zero National Health Service	Achieved a reduction of 26% carbon footprint, and a decrease of 64% in emissions per inpatient finished admission episode between 1990-2020

In summary, effective resilience demands synergy between community participation and institutional capacity. By combining technology, governance, and social engagement, these multi-scale interventions build adaptive systems capable of withstanding intensifying climate extremes.

Environmental and public policy interventions. In response to the growing challenges of climate change, countries and regions worldwide have implemented various environmental and public policy measures to safeguard public health, improve quality of life, and address the inequalities exacerbated by environmental and climate change. This section explores several examples of environmental and public policy interventions at global and local levels, spanning climate change strategies, urban planning, heat health adaptation, sustainable transport, and decarbonising health systems (Table 4).

International climate policies. Global climate policy negotiations are crucial in fostering international collective efforts for mitigation and adaptation. The United Nations Framework Convention on Climate Change (UNFCCC), which came into force in 1994, is the UN process for negotiating and implementing an agreement to curb climate change.[218] The UNFCCC's work currently focuses on implementing the Paris Agreement, which aim to limit the temperature rise to 1.5°C above pre-industrial levels. Since its adoption in 2015, many countries have established carbon neutrality targets through National Determined Contributions (NDCs), and 60 countries have submitted their National Adaptation Plans by November 2024.[219]

Climate finance is also a vital element of the Paris Agreement, with the Green Climate Fund (GCF) supporting developing countries in realizing their NDCs.[220] The GCF has supported over 280 projects in developing countries, valued at more than 16 billion USD. In 2023, the GCF approved adaptation projects with potential health benefits totalling 423 million USD, a 137% increase compared to 2021.[3] Mandated to invest half in mitigation and half in adaptation, the GCF projects are anticipated to reduce 3.1 billion tonnes of CO_2 equivalent and increase resilience for 1 billion people. It is vital to boost green financial policies to realise the pathways to increase climate.[221]

Meanwhile, evidence on the public health implications of achieving the Paris Agreement indicate that integrating health more explicitly in the NDCs and climate policies could yield substantial health benefits,[222] a priority reinforced by the World Health Organisation (WHO) through its engagement in the United Nations Climate Change Conference of the Parties (COP) negotiations and the COP29 Special Report on Climate Change and Health.[223]

Greener cities. Cities are both major contributors to climate change and highly exposed to its impacts, but they also offer critical opportunities for mitigation and adaptation as hubs of innovation and policy action. Substantial evidence supporting that increased urban green space benefits human health and its effectiveness in advancing health equity, even though most studies are concentrated in high-income countries.[224] For example, meeting the WHO recommendation for green space access could prevent nearly 43,000 deaths per year in 31 European countries.[225] The primary mechanisms behind these beneficial impacts include an improved environment and increased physical activity mediated by green spaces, which help reduce physical and psychological risks. Urban nature-based recreations have also brought mental health benefits and enhanced social connections.[226] Noticeable evidence also examines the relationship between green space and loneliness, an emerging global epidemic closely influenced by the urban environment.[227–228]

Evidence on green infrastructures (e.g. green roofs and walls) and low-carbon city policies (e.g. renewable energy) remains limited and inconsistent, with health impacts often understudied.[229–230] The evaluations of China's Air Pollution Prevention and Control Action Plan from 2013-2017 indicate mixed outcomes on air pollution reduction (significant improvement in $PM_{2.5}$, PM_{10} and SO_2 but not NO_2 and O_3), positive health benefits (avoided 470,000 deaths) nationally,[231–232] and substantial economic benefits at a local level.[233] There is an urgent need to advance health-oriented city planning policy and governance, especially in Low-and-Middle-Income countries (LMICs).[234]

Heat-Health Adaptation Plans. Rising temperatures due to climate change poses significant health threats, including heat-related illnesses, cardiovascular problems, infectious diseases, mental illnesses and deaths, while many of which are preventable.[235–236] Heat-Health Adaptation Plans (HHAPs) support better preparedness and respond to extreme heat through measures such as heat-health warning systems (HHWS), coordinating emergency responses, improving access to cooling, and building resilience to heat.[237] While many countries, especially high-income countries, have developed or updated their HHAPs at local or regional governments, few countries have a national HHAP, such as France's National Heatwave Plan (Plan National Canicule), which was introduced in 2004 after the deadly 2003 heatwave.[238] Evidence on the effectiveness of HHAPs revealed mixed outcomes with noteworthy methodological challenges, and major gaps remain in resource-limited settings.[239] A more comprehensive, multi-scale understanding of the thermal environment is therefore essential for developing sustainable solutions to protect people's health from heat.[240]

Active, sustainable transport. Transitioning from fossil fuel-dependent transportation to active transport (e.g. walking, cycling, and public transport) reduces carbon emissions, air pollution, and associated health risks.[241] For example, if 50% of travellers shifted to walking/cycling mode, it could reduce London's adult premature deaths by 2.5%.[242] Shifting 40% of private car drivers to active transport can reduce the annual average $PM_{2.5}$ by 0.4 μg/m^3 and prevent over 500 deaths per year in Adelaide, an Australian city with a 1.5 million population.[243]

Sustainable public transport systems further mitigate climate-related health impacts by reducing congestion, noise, and urban heat island effects while fostering more resilient, walkable, and liveable environments, with strong potential in LMICs, such as the new Tehran Transportation Master Plan in Iran,[244] the bust rapid transit in Vietnam,[245] and the mass rapid transit system in Malaysia [246] (see more details in Table 4). However, evidence on their effects on health inequity remains limited, and methodological and multisectoral data constraints continue to challenge health impact assessments.[247]

Decarbonising health systems. The health sector provides necessary services while contributing over 4% of global net emissions.[248–249] The WHO has recognized the need and the opportunity to build climate-resilient, low-carbon, and sustainable healthcare systems in responding to climate change.[250] The UK's National Health Service (NHS) provides the leading example, becoming the first health system to embed net zero into legislation in 2022, and implementing system-wide decarbonization strategies. As a result, the NHS reduce its carbon footprint by 26%, and emissions per inpatient finished admission by 64% between 1990 and 2020,[251–252] offering a model for many other countries to follow.

This section highlights the importance of win-win climate policy interventions in achieving environmental, health and economic co-benefits.[253] The co-benefits approach offers an integrated framework that supports cross-sector collaboration and ambitious action, particularly in policies targeting green infrastructure, energy, and transport.[247,254–255] Well-designed clean energy policy can simultaneously reduce climate risks, support adaptation, and improve health, yet co-benefit evidence remains underused in policymaking, leading to suboptimal outcomes.[256–257] To address the challenges, recent initiatives including the Lancet Pathfinder Commission and Health in All Policies (HiAP), have been proposed to embed health considerations across climate policy to accelerate the transition toward an equitable, healthy net-zero future.[258]

Future needs

Climate-related extreme events are emerging as increasingly important drivers of global health risk. Although substantial progress has been made in documenting their impacts, the current evidence base remains uneven and fragmented across hazards, health outcomes, and regions, and is not yet sufficient to guide comprehensive adaptation and resilience planning. Several key areas therefore warrant prioritisation in future research.

First, most studies available on the health effects of climate change have generally been based in high-income countries, but evidence is relatively scarce in low- and middle-income countries, especially those in vulnerable regions (e.g., Africa and Southeast Asia). These regions often face higher baseline disease burdens, constrained health-system capacity, and fewer adaptive resources, meaning that climate shocks may translate into disproportionately greater health impacts. Expanding high-quality, population-based research in these settings is essential not only to fill geographical gaps, but to address global inequities in exposure, vulnerability, and adaptation benefits.

Second, heterogeneity in exposure assessment, health metrics, modelling strategies, and temporal definitions has constrained comparability across regions and time periods. Future research would benefit from harmonised methodological frameworks that account for socioeconomic development, demographic change, technological advances, urbanisation, and adaptive capacity. Life-course designs, longitudinal studies, and causal inference approaches will be particularly valuable for identifying both short- and long-term health risks and for characterising cumulative exposure trajectories over time.

Third, most existing research has focused on single-hazard exposures such as heatwaves, floods, or wildfires, while the health implications of compound and cascading climate extremes remain under-explored. Concurrent or sequential events, such as heat accompanied by wildfire smoke, drought-heat extremes, wet-heat extremes, or compound flooding, are projected to occur with increasing frequency.[259] Understanding interactions, nonlinearities, thresholds, and amplification mechanisms in health outcomes represents an important emerging research frontier and is essential for designing adaptation strategies that are resilient to multiple hazards.

Fourth, the current evidence base remains heavily weighted toward mortality outcomes, despite growing recognition of the substantial burden of climate-related morbidity, disability, reduced labour productivity, and mental health effects. Important gaps include chronic disease exacerbations, neurodevelopmental and neurodegenerative outcomes, cumulative life-course impacts, and potential intergenerational consequences. Future research should quantify the contribution of climate extremes to the burden of disease at global, regional, and national levels, with particular attention to children, older adults, people living with chronic or mental illness, Indigenous communities, migrants, and populations with limited adaptive resources.

Fifth, the effectiveness, equity implications, and unintended consequences of adaptation strategies are not well understood. Many interventions are implemented without rigorous evaluation, and some may inadvertently shift risk across populations or across time, for example through reliance on energy-intensive cooling, displacement and housing instability, green-space-driven gentrification, or insurance models that exclude high-risk groups. Future research should determine which interventions work, for whom, under what circumstances, and at what social and environmental cost, while explicitly assessing the potential for maladaptation.

Sixth, stronger evidence is needed to support climate-resilient health systems. Priorities include resilience metrics, continuity of essential services, secure supply chains and digital systems, and workforce protection. Implementation-focused research will be essential to bridge the gap between evidence and practice.

Finally, climate–health research must increasingly integrate epidemiology with climate science, behavioural and social sciences, economics, and policy analysis, while engaging directly with communities, health practitioners, and decision-makers. Co-production approaches, particularly those grounded in Indigenous knowledge, community experience, and local governance, will be essential to ensure that research priorities reflect lived realities and to strengthen trust, relevance, and uptake.

Taken together, these priorities signal a maturing field that is moving beyond documenting risk toward building climate-resilient, equitable, and learning health systems. A future climate-health research agenda will need to incorporate cumulative and life-course exposures, multi-hazard realities, structural inequities, and the complex interplay between adaptation, behaviour, and governance. By advancing decision-relevant, interdisciplinary, and justice-informed science, the climate-health community can more effectively support prevention, preparedness, and adaptation in an era of accelerating climate extremes.

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AUTHOR CONTRIBUTIONS

PY, SL, and YG conceived and designed the study. PY led the literature search, evidence synthesis, and manuscript drafting. YL was primarily responsible for figure conceptualization and preparation. YX, CH, YH, LH, TL, BA, DP, BC, YHL, ZL, AT, QF, HW, LM, JH, TTS, YZ, and ST contributed to literature search and manuscript drafting. All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

Yuming Guo is an Editorial Board member of The Innovation Medicine and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.

DATA AND CODE AVAILABILITY

No new data were created or analyzed in this study.