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Understanding the global landscape of heat early warning systems

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About the Zurich Climate Resilience Alliance

The Zurich Climate Resilience Alliance is a collaboration between humanitarian, NGO, research, and private sector partners working to build resilience to climate hazards in rural and urban contexts.

Formerly the Zurich Flood Resilience Alliance, we have over a decade of experience in generating evidence of communities' current levels of climate resilience and identifying appropriate solutions.

Through long-term community programmes, new research and stakeholder influencing, we strive to deliver systemic change at scale and realize our vision of a world in which communities are more resilient to climate hazards, and able to thrive.

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Abbreviations

AI	Artificial intelligence
EAP	Early action protocol
EJN	Earth Journalism Network
EW4All	Early Warnings for All
EWS	Early warning system
FEWS	Flood early warning system
GESI	Gender equality and social inclusion
GHHIN	Global Heat Health Information Network
HAP	Heat action plan
HEWS	Heat early warning system
HHAP	Heat-health action plan
HHWS	Heat-health warning system
HI	Heat index
IBF	Impact-based forecasting
MHEWS	Multi-hazard early warning system
NEAP	National Early Action Protocol
NMHS	National Meteorological and Hydrological Service
SOFF	Systematic Observations Financing Facility
UHI	Urban heat island
UK	United Kingdom
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
USA	United States of America
WBGT	Wet-bulb globe temperature
WHO	World Health Organization
WMO	World Meteorological Organization

Executive summary

Extreme heat is one of the most dangerous yet under-prioritized climate hazards worldwide. The past 11 years have been the hottest on record, and extreme heat is increasing in frequency, duration, intensity, and geographic extent. Each year, extreme heat contributes to hundreds of thousands of deaths and causes wide-ranging impacts across public health, labour productivity, agriculture, livelihoods, energy supply, infrastructure, and ecosystems. These impacts are uneven, with socially, economically, and physiologically vulnerable populations facing disproportionate risks.

Heat early warning systems (HEWSs) are a critical tool to anticipate dangerous heat conditions and enable governments and communities to take timely, protective action. Since the early 2000s, the number of systems has increased rapidly, often in response to major heat-related health impacts, but progress remains uneven and systems are highly diverse. This report provides a global overview of HEWSs, examining where they exist, how they are designed and operated, and their challenges and opportunities. It assesses the state of systems through the four core pillars of early warning systems (EWSs) and enabling components, drawing on peer-reviewed and non-academic evidence.

The results show that, while heat-related risk knowledge has expanded, particularly in understanding heat–health relationships, important gaps remain across sectors and regions, limiting the ability of systems to fully capture who is at risk and why. Forecasting skill has improved substantially, with reliable temperature predictions available up to one week in advance in many regions. However, there is still wide variation in how heat is measured and how thresholds are set, and these are not always periodically updated as climate conditions and societal vulnerabilities change.

Communication remains a challenge: heat is often underestimated and normalized; technical terminology is not well understood; and warnings tend to focus on temperatures rather than clearly explaining impacts and what people should do. While heat action plans (HAP) and anticipatory approaches are expanding, many countries still lack them; and where they do exist, implementation gaps remain, including limited cross-sectoral coordination and insufficient sustained financing to ensure that warnings translate into protective action.

Heat also interacts with other hazards, such as drought, wildfire, and air pollution, but these risks are rarely addressed together in practice. Social and gender inequalities shape who is most exposed and vulnerable, yet inclusive design is often insufficient, and community engagement, especially in early design stages, remains limited. Governance fragmentation, unclear mandates, and short-term project-based financing undermine continuity and long-term resilience.

At the same time, innovations are emerging. Impact-based forecasting (IBF) offers the potential to predict impacts such as health outcomes rather than temperatures alone. Personalized and targeted warning systems are being explored but require careful attention to governance responsibility and equitable access to ensure that benefits reach those most at risk. Artificial intelligence (AI) presents opportunities to enhance forecasting, exposure and vulnerability mapping, and tailored communication, yet its application to heat remains limited compared to other hazards.

To address these gaps, this report outlines 10 recommendations for strengthening HEWSs globally. Key priorities include embedding community participation and inclusive design, strengthening heat risk knowledge across sectors, improving the selection and use of heat metrics and thresholds, ensuring warnings translate into timely and coordinated action through national to local HAPs, and strengthening governance, financing, and continuous learning. As climate change intensifies extreme heat, expanding and strengthening HEWSs will be essential to reduce preventable loss of life and livelihoods and safeguard critical sectors worldwide.

Introduction

Heat risks are rising around the world

Extreme heat is rapidly becoming one of the most dangerous climate hazards facing the world today. The last 11 years have been the hottest on record, and global temperature records are being broken every year (Copernicus Climate Change Service, 2026). Notably, heat extremes are rising even faster than average warming, and extreme heat is becoming more frequent, hotter, longer, and covering larger areas around the world (IPCC, 2023). In some regions, the combination of high temperatures with high humidity is leading to seasonal or chronic exposure to dangerous levels of heat stress (Cruz et al., 2025). Climate projections clearly show that these trends will continue and likely intensify in the coming decades (Domeisen et al., 2023).

Extreme heat has devastating impacts across multiple sectors. Extreme heat is among the deadliest disasters, threatening human health and well-being, and causing at least 489,000 deaths annually worldwide, a number likely far higher due to under-reporting and limited health records (Campbell et al., 2018; Zhao et al., 2021). Heat can cause heat exhaustion and heat-stroke, and it can also worsen existing conditions such as heart, lung, and kidney disease, leading to increases in hospitalizations and mortality. Heat affects pregnancy and birth outcomes, increasing the risk of stillbirth and preterm labour, and it also affects young children (Syed et al., 2022). Heat disrupts sleep and cognitive performance, and it has been linked to declines in learning among school children and increased school absenteeism (McGregor, 2024) and school disruptions (Arrighi et al., 2025). It also affects mental health, contributing to irritability, anxiety, depression, and increased suicide risk, and it has been associated with rises in gender-based violence (Van Daalen et al., 2022; McGregor, 2024; Arrighi et al., 2025).

Beyond impacting health, extreme heat also reduces labour capacity and productivity, and it disrupts energy and transport systems, education, water resources, infrastructure, and tourism, with each sector carrying substantial economic damages and losses (McGregor, 2024). In 2023 alone, extreme heat led to US$835 bn in lost income due to reduced labour capacity (Romanello et al., 2024). Extreme heat also has profound impacts on agriculture, food systems, and rural livelihoods. Heat stress can reduce crop yields, affect livestock health and productivity, and increase mortality in domesticated animals and wildlife, while also stressing terrestrial and marine ecosystems (McGregor, 2024). These effects undermine food security, ecosystem stability, and income security for many households, particularly in low- and middle-income countries where agriculture remains a primary source of livelihood. A single heatwave may reduce agricultural productivity by up to 50 per cent, while

Figure 1 In Kolkata's scorching April heat, water is scarce (winner of the Global Heat Health Information Network (GHHIN)–Earth Journalism Network (EJN) Extreme Heat Photo Contest 2025). Photo: Ayanava Sil (India)

agricultural workers face a dramatically elevated risk of heat-related death, up to 35 times higher than other workers (WMO and FAO, 2025). Smallholder farmers and agricultural workers are among the most exposed due to prolonged outdoor work, limited access to cooling, and high dependence on climate-sensitive livelihoods. Globally, heat threatens the livelihoods of an estimated 1.23 billion people (WMO and FAO, 2025).

These impacts are not evenly distributed. Risk is shaped, beyond the hazard itself, by exposure, vulnerability, and access to resources. Certain groups are more at risk due to physiological, social, and structural factors. Extreme heat disproportionately affects groups such as older persons, low-income communities, outdoor workers, children, pregnant women, people with medical or chronic illnesses, and racially and ethnically marginalized groups (OCHA, 2022; Deivanayagam et al., 2023).

Given the scale of these impacts, robust HEWSs are essential to anticipate heat and trigger timely, protective action across sectors.

The need for Heat Early Warning Systems worldwide

As heat risks continue to grow, strengthening HEWSs is critical to reducing preventable impacts. HEWSs use meteorological forecasts to provide advance notice of heat, allowing governments and communities to prepare before impacts occur. Although HEWSs can exist on their own, they are usually part of and most effective when embedded in a wider, longer-term HAP, heat-health action plan (HHAP), or integrated into a broader multi-hazard early warning system (MHEWS) (Matthies et al., 2008; McGregor et al., 2015). The Intergovernmental Panel on Climate Change states with 'high confidence' that HHAPs that include early warning and response systems represent key adaptation options to extreme heat. Next to HHAPs, early warning and response systems are equally important for protecting other sectors such as infrastructure, agriculture, and rural livelihoods.

In recognition of the escalating risk, the United Nations (UN) Secretary General issued a call to action on extreme heat in 2024, urging governments and partners to prioritize protection of vulnerable populations. A central component of this call is the need to establish and expand HEWS, in line with the Early Warnings for All (EW4All) initiative, ensuring that at-risk populations receive timely alerts that include actionable guidance and access to support.

Despite progress, global coverage remains uneven. A 2023 World Meteorological Organization (WMO) survey found that 54 per cent of National Meteorological and Hydrological Services (NMHSs) issue extreme heat warnings (Royé et al., 2026). Most of these are temperature-based alerts (40 per cent), with far fewer countries using thermal indices that account for humidity and human heat load, and only a very small number using heatwave intensity metrics (for more on heatwave intensity, see Nairn and Mason, 2025). Even where heat warnings exist, they often remain generic and at the population level and are not consistently linked to predefined early actions or tailored to reflect differential vulnerability across groups, sectors, or locations. Yet the benefits of strong heat-warning systems are large: scaling up heat-health warning systems (HHWSs) worldwide could save nearly 100,000 lives annually, according to estimates from the World Health Organization (WHO) and the WMO (WHO, 2024).

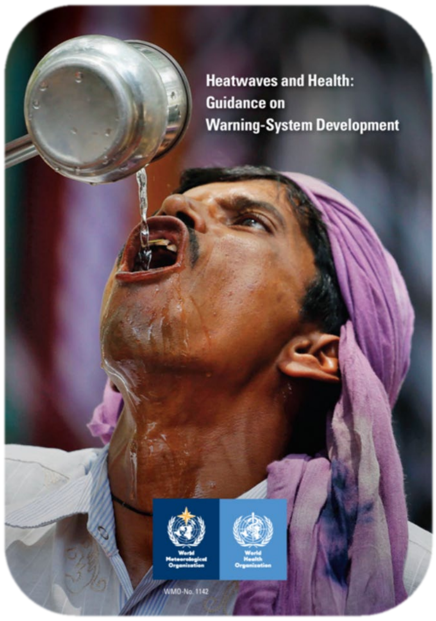

Figure 2 Heatwaves and health: guidance on warning-system development. Source: McGregor et al. (2015)

In 2015, the WHO and WMO published the first comprehensive guidance for the development of early warning systems for extreme heat (McGregor et al., 2015), which is currently being updated, with a new version expected in 2026. This report builds on existing global frameworks, focusing on the current state of systems and identifying major trends and gaps across regions and contexts.

Methodology and scope of this report

This report provides a global overview of HEWSs, examining how countries define, monitor, forecast, communicate, and respond to extreme heat. It highlights common design features and innovations and identifies key challenges and opportunities for strengthening and scaling systems. Overall, this report aims to answer the following questions:

1. Where do HEWSs exist globally, and how are they designed?
2. What is the current state of HEWSs across the four EWS pillars and enabling components, including challenges and gaps?
3. What are the priority recommendations for strengthening HEWSs worldwide?

Narrative review approach

We conducted a narrative review to synthesize the breadth of research and practice on HEWSs. A narrative review is a qualitative and interpretative synthesis of existing literature and practice. This approach is particularly suitable in emerging and interdisciplinary fields where evidence is heterogeneous and operational knowledge is not consistently documented. By examining peer-reviewed studies, grey literature, and operational materials, we qualitatively assessed how HEWSs are defined and implemented worldwide. This approach allowed us to bring together diverse sources and identify common patterns, gaps, and emerging trends.

Literature search and sources

To inform the review, we searched peer-reviewed literature (through major journal databases such as ScienceDirect, SpringerLink, Scopus) and grey literature (e.g. government reports, NGO publications, and technical documents). Sources other than peer-reviewed papers were essential, given the operational nature of HEWSs and relatively limited academic literature. Insights from recent webinars, expert consultations, and practitioner discussions were also incorporated to capture emerging practices not yet reflected in the literature. However, the availability of information varies widely across contexts, and this report may therefore over-represent countries where HEWSs are more documented, while systems in countries with limited reporting, documentation, or publication may therefore be under-represented.

In parallel to this global review, the Zurich Climate Resilience Alliance has developed a series of eight country-level HEWS profiles across diverse climatic and institutional contexts, including **Bangladesh, Jordan, Mexico, Nepal, Pakistan, the Philippines, Senegal, and Vietnam**. These case studies provide in-depth insights into national systems and operational challenges. While the findings are not synthesized in this report, they complement the global analysis and will be published separately to support country-level learning and exchange.

Understanding HEWSs

This section provides an overview of how Heat Early Warning Systems work, outlining the main types used worldwide and the key components that make them effective. It begins by defining HEWSs, briefly tracing their development and explaining why health has often been the primary focus. It then describes the status of the four pillars and four enabling components that underpin effective HEWSs. These components form the conceptual backbone for understanding how HEWSs are designed, where gaps commonly arise, and how they can be strengthened.

What is a heat early warning system?

HEWSs are a type of EWS designed to anticipate dangerous heat conditions and support timely action. The official definition by the UN Office for Disaster Risk Reduction (UNDRR) describes an EWS as

> *'An integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events'*. (UNDRR, 2017: para 1)

Like other EWSs, HEWSs are integrated systems that combine hazard monitoring, forecasting and prediction, communication and dissemination, and preparedness activities.

Different types of heat early warning systems

The WMO/WHO's forthcoming *Heatwaves and Health: Guidance on Warning-System Development* highlights that there are multiple types of HEWSs, which can be understood along key dimensions such as the type of meteorological indicator(s) used and whether warnings are explicitly linked to health outcomes. The first two types of HEWSs describe the type of meteorological (hazard-based) system, while the third reflects the extent to which systems are linked to health impacts:

1. **Extreme temperature or heatwave (temperature-based) warning systems**
   These are climate- and hazard-based systems that rely on extreme air temperature thresholds of maximum and/or minimum temperature to trigger warnings. Some use single maximum temperature thresholds to identify unusually hot conditions (e.g. extreme temperature), while others combine maximum and minimum temperatures over several days to capture sustained heat across the day-night cycle (e.g. heatwaves). Because they depend on standard meteorological observations and forecasts, they are relatively straightforward to implement and are widely used operationally.

2. **Thermal (weather) warning systems**
   These systems are also meteorological in nature but use thermal stress indicators that combine multiple variables, such as temperature, humidity, wind, and solar radiation, to better represent how heat is experienced by the human body. Common indices include the wet-bulb globe temperature (WBGT) and the heat index (HI). These systems can capture hazardous heat conditions even when air temperature alone is not extreme, but they require more complex data inputs and modelling.

3. **Heat-health warning systems**
   Both temperature-based and thermal warning systems can be linked to health outcomes (e.g. typically mortality) to form HHWSs. These are impact-based systems that calibrate meteorological conditions against observed health impacts to define thresholds. Most often,

mortality is used, as it is more widely available and is typically estimated using excess mortality approaches. However, countries employ a wide range of methods, and no standardized approach exists (Royé et al., 2026). While more data intensive, requiring epidemiological data and analysis, HHWSs provide warnings that are more directly relevant for protecting public health.

In this report, we use the term **heat early warning system (HEWS) as an umbrella term** to cover all types of heat EWSs. Where necessary, we refer to the subtype (e.g. HHWS); however, for simplicity and readability, the terms 'HEWS' or 'heat EWS' refer to any system designed to anticipate heat and trigger protective action.

While the structure of HEWSs varies widely across countries, most systems share several basic features. Although many of the earliest systems were developed at the city level, most systems now operate nationally, with the NMHS providing warnings that are often issued at regional, provincial, or state scales. These warnings act as triggers for a broader set of preparedness and response actions that can be led by health authorities, disaster management agencies, local governments, and humanitarian actors. In many countries, heat warnings are embedded within HAPs or HHAPs, which outline the concrete measures to be activated before and during a heat event (Figure 3).

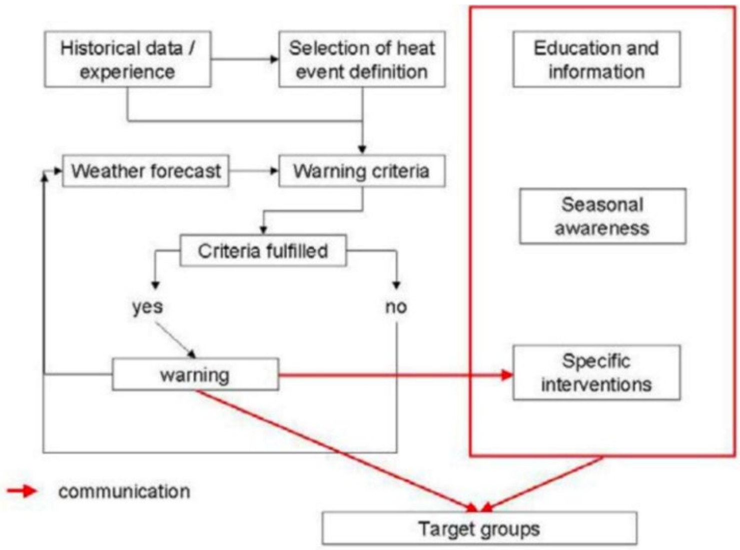

Figure 3 Operation of a typical heat EWS within a wider HAP (elements in red box). Source: McGregor et al. (2015)

Why health has often been the focus of public HEWSs

Many HEWSs have been developed primarily to protect public health, often following major heatwaves with significant health impacts. This reflects the growing global recognition of heat as a major public health hazard, with relatively strong epidemiological evidence linking extreme heat to mortality and other adverse health outcomes. As a result, public warning systems for heat have often been designed through a health lens, aiming to warn for population-level health risk.

Heat risk extends well beyond the health sector and affects sectors such as agriculture, education, water and energy systems, infrastructure, ecosystems, and livelihoods. Most national warning systems are formally mandated to serve all of society. While sector-specific decision protocols for extreme heat may exist in countries, they are typically embedded in internal operational procedures rather than integrated into public-facing warning systems. As climate change increases the frequency and severity of extreme heat, demand for tailored heat forecasts and thresholds, next to public-facing warning systems, is expected to grow. This highlights the need for more accurate, sector-relevant heat indicators and forecasts, ideally linked to sectoral impact data, to better understand when and how to trigger effective actions across different sectors and user groups.

A brief history of HEWSs around the world

Since the late 20th century, efforts began to develop warning systems for extreme heat, often as a reaction to an impactful heatwave event and growing recognition of heat as a public-health threat. Figure 4 shows a brief history of HEWSs for those of which the year of development is known. The first systems were typically developed at the city scale and emerged from the health sector, with the primary goal of preventing deaths during heatwaves. One of the first documented examples was launched in Philadelphia in 1995, followed shortly by other North American cities. Early city-scale initiatives appeared in Lisbon in 1999, and in Shanghai, Toronto, and Rome in the early 2000s (Kalkstein et al., 1996; Pascal et al., 2006; Leite et al., 2020; Kotharkar and Ghosh, 2022). Hong Kong has operated the 'Very Hot Weather Warning', based on maximum temperatures, since 2000 (Fai et al., 2026).

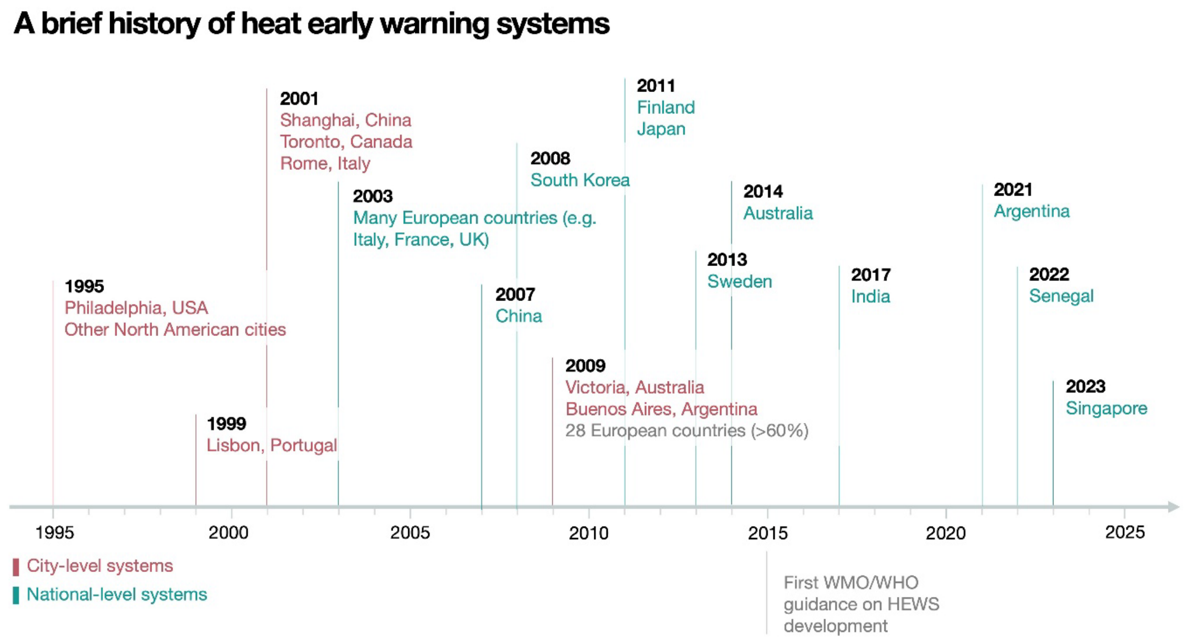

Figure 4 A brief history of HEWSs around the world (note that this timeline includes selected examples based on available documentation; many systems are not shown due to limited reporting on the start of the system's development)

The 2003 European heatwave, which caused more than 70,000 excess deaths across the continent, marked a turning point. In its aftermath, France introduced one of the first national HHWSs, followed by many other European countries such as the United Kingdom (UK), Germany, and Belgium (Casanueva et al., 2019). By 2009, 28 European countries operated HEWSs, based either on epidemiological evidence (linking temperature to mortality) or on climatological thresholds and temperature anomalies. As of 2025, all European Union countries issue heat warnings, except Iceland, Norway, and a few small territories.

In South Asia, the unprecedented 2010 heatwave in India and Pakistan spurred regional action, with Ahmedabad's HAP (2013) becoming the first in the region, inspiring the development of India's national heat-warning system later in the decade (Kotharkar and Ghosh, 2022). China and South Korea developed national heat-warning systems in 2007 and 2008, respectively (Chae and Park, 2021), and Japan introduced a Hot Temperature Alert in 2011 for days with forecast highs above 35°C (which was replaced by a WBGT-based Heatstroke Alert in 2020). Singapore also started issuing WBGT-based heat warnings in 2023.

Across Africa, Burkina Faso and Senegal stand out as early examples, starting work on HHWSs around 2015, with Senegal publishing heatwave bulletins in 2022 (USAID, 2024). While many other African countries currently issue temperature or heat warnings, there is little documentation on when and how systems are designed. In Australia, HHWSs were introduced in South Australia and Victoria after the 2009 extreme heatwave. In early 2014, a national seven-day heatwave severity forecast service was introduced (by the Australian Bureau of Meteorology), which became the national heatwave warning service in late 2022. In Argentina, the National Weather Service introduced a city-level HEWS for Buenos Aires in 2009, which was expanded to country-wide warnings in 2021 (WMO, 2023).

The most recent global survey conducted by WMO in 2023 indicates that approximately 54 per cent of countries report issuing some form of extreme heat warning (WMO, 2023). Building on earlier surveys from 2021 (WMO) and 2022 (WHO), a global map was developed using self-reported information from national meteorological and health authorities to indicate whether countries operate an HEWS (orange), an HHWS (dark blue), or both (light blue) (Figure 5). Due to differing definitions and interpretations of HEWSs and HHWSs and slightly outdated information, the map likely does not fully reflect the current or complete global landscape of HEWSs.

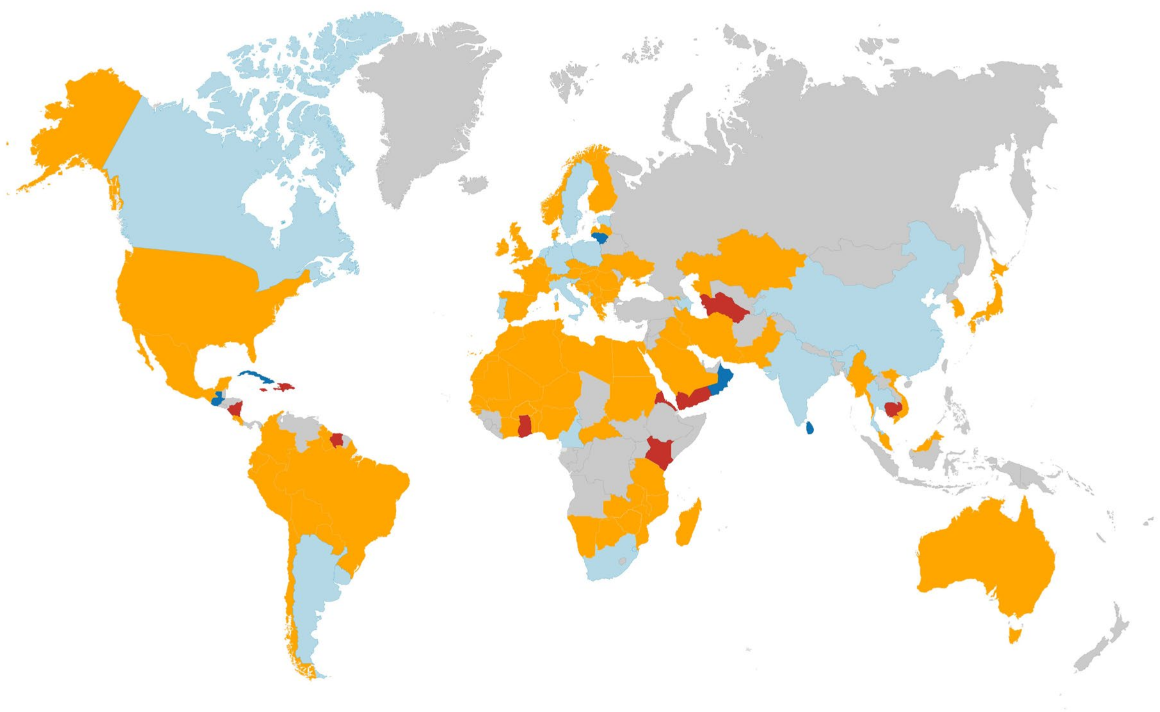

Figure 5 Global map of HEWSs and HHWSs. Light blue: both HEWSs and HHWSs; orange: only HEWSs; dark blue: only HHWSs; red: no warning system; grey: no data. Adapted from Yoo et al. (2023). Data source: 2021 WMO survey (67.7 per cent response rate; WMO, 2023) and 2022 WHO survey (Yoo et al., 2023)

The components of an effective HEWS

Effective HEWSs are people-centred and end to end, meaning they link scientific forecasts to timely and protective actions by those at risk. EWSs typically consist of four core pillars (Figure 6):

1. **Pillar 1: Disaster risk knowledge** – understanding the hazard, exposure of people, infrastructure, and public services, and vulnerabilities through risk assessments and data analysis.
2. **Pillar 2: Observations, monitoring, analysis, and forecasting** – generating timely and reliable forecasts and warnings.
3. **Pillar 3: Warning dissemination and communication** – ensuring alerts are communicated clearly, through trusted and accessible channels, to all at-risk populations.
4. **Pillar 4: Preparedness and response capabilities** – enabling authorities, organizations, and communities to take timely, effective, and inclusive action when warnings are issued.

Figure 6 The four pillars and four enabling components of a people-centred EWS. Source: Zurich Climate Resilience Alliance

These four pillars are supported by **four enabling components** that ensure EWSs are sustainable, inclusive, and coherent across scales. A **multi-hazard approach** means that EWSs cover multiple hazards (e.g. floods, droughts, extreme heat, wildfires) and are aligned with broader national early warning and disaster risk management frameworks, rather than operating as separate hazard 'silos'. A multi-hazard approach also means explicitly accounting for how hazards can interact across time and space, occurring simultaneously, in sequence, or through cascading impacts. **Gender and social inequalities addressed inclusively** require systems that actively confront structural barriers, so that all groups, especially those most at risk, are reached, able to access and use warnings, and are meaningfully represented in the design and evaluation of the EWS. **Local community involvement** promotes participation and co-production in all aspects of the warning chain, from risk assessment to threshold and communication design, as well as preparedness planning, strengthening trust, behavioural uptake, and local ownership. **Effective governance and institutions** provide the coordination, accountability, and sustained resources needed to operate and maintain EWSs across sectors and levels of decision-making.

For EWSs to work effectively, all components must function together and reinforce one another. While the four pillars provide a useful framework, in practice, EWSs operate as interconnected and dynamic processes involving multiple actors, services, and institutions across scales. Risk knowledge, forecasting, communication, and preparedness are not sequential steps but operate simultaneously, shaping how warnings are interpreted and translated into action. Viewing an HEWS as a multilayered ecosystem rather than a linear chain of steps, aligned with the concept of a ‘value cycle’ rather than a ‘value chain’, emphasizes the importance of coordination, continuous and iterative learning, shared ownership, and aligned communication across actors. At the same time, the overall effectiveness of an EWS is determined by its weakest component. A weakness in any one element, whether gaps in observational capacity, unclear or inaccessible communication, or insufficient preparedness and response, can undermine the entire system (Golding, 2022). Even the most accurate forecast will not reduce impacts if warnings do not reach people or if they are not linked to predefined action plans.

The following sections examine each of the four pillars in more detail, focusing on their application to HEWSs. For each pillar, guiding questions are provided in Appendix A to support assessment and strengthening efforts.

Figure 7 Intuitive shade, Los Angeles, United States of America (USA) (from the GHHIN-EJN Extreme Heat Photo Contest 2025). Photo: Shanley Kellis

Pillar 1: Disaster risk knowledge

Risk knowledge is the foundation of any effective EWS. It ensures that information on hazards, exposure, and vulnerability is systematically collected and used to understand who and what is at risk, how, where, and why. In the context of extreme heat, impacts can vary significantly within the same region, across population groups, between buildings, and over time. Despite growing evidence, significant gaps remain in understanding how heat impacts different groups, how vulnerability is distributed, and how risks are changing over time.

At the national level, responsibility for this pillar is typically shared across disaster risk management authorities, meteorological services, health institutions, statistical agencies, and research organizations, often requiring strong coordination mechanisms to integrate climate, health, and socio-economic data. Within the EW4All initiative, this pillar is globally led by the UNDRR, reflecting its mandate to support countries in strengthening risk assessment, loss and damage data, and multi-hazard risk profiling to inform early warning and anticipatory action.

Understanding heat risks

Heat risk knowledge provides the foundation for defining warning thresholds, identifying priority populations and locations, and guiding targeted preparedness, communication, and early action across sectors. It rests on three interconnected components: understanding the **hazard** itself (including historical trends, future projections, and the characteristics of extreme heat events); understanding **exposure** (who and what is located in areas experiencing high temperatures); and understanding **vulnerability** (which groups, assets, and systems are more susceptible to harm due to underlying social, economic, environmental, and infrastructural risk factors that influence their sensitivity and capacity to cope, adapt, and recover). It is also important to understand compounding and cascading impacts.

Developing this knowledge requires the integration of multiple types of evidence. Heat risk knowledge can be built from multiple data sources, including meteorological information (e.g. long-term temperature records and climate projections), impact data (e.g. mortality, morbidity, and sectoral impacts), exposure and vulnerability indicators (e.g. age, health status, housing quality, access to green or cool spaces, and urban heat island (UHI)[1] intensity), and community-based knowledge and qualitative insights from local actors. Combining these sources enables a more comprehensive and context-specific understanding of risk.

Risk knowledge on when and how heat becomes harmful across different sectors can support the development of locally relevant thresholds and early actions. For the health sector, this is often informed by epidemiological analyses linking temperature to mortality. For example, a study in Mexico found that 75 per cent of heat-related deaths occur amongst people under 35 years old (Wilson et al., 2024), highlighting the importance of age-specific preparedness. In Bangladesh, heat risk knowledge was developed by combining historical climate analysis with sectoral impact evidence and participatory approaches, including field investigations and stakeholder consultations (EIMS, 2025). This process helped identify how heat affects agriculture, livestock, and livelihoods, as well as the conditions under which impacts become significant. It also enabled the co-development of context-specific anticipatory actions, such as crop and livestock management measures, livelihood support, and targeted health interventions.

Heat risk perception and awareness

Risk knowledge also includes understanding how heat is perceived. Although awareness of climate change and heat is increasing, extreme heat still remains widely underestimated as a serious hazard (Arrighi et al., 2025). People may normalize high temperatures, attribute them to non-climatic causes (e.g. religious or spiritual explanations), or fail to connect them to significant health and livelihood risks. When heat is perceived as an uncontrollable external threat, this can lead to disempowerment and reduce motivation to take action. Risk perception varies across gender, age, disability, occupation, location, socio-economic status, and other intersecting identities, influencing whether warnings are received, understood, and acted upon. It is also shaped by past experience and geographic context. Evidence from a post-event review in Australia suggests that extreme heat is normalized and framed as something people should 'deal with' on their own (MacClune et al., 2026). Understanding these perception gaps is therefore central to effective preparedness and adaptive behaviour (Hass et al., 2021; McLoughlin et al., 2023). Still, there are large research gaps, as further detailed in the Pillar 1 Gaps and challenges section (page 15).

[1] A UHI is a phenomenon whereby urban areas experience higher temperatures than surrounding rural areas due to factors such as built surfaces, reduced vegetation, and heat generated by human activities.

Unlike floods or storms, heat is often described as an invisible or 'silent' hazard (Nunes, 2024). The heat itself is not directly observable, and many of its impacts are diffuse, delayed, or indirect, making risks harder to perceive, communicate, and attribute. Moreover, heat is frequently portrayed as enjoyable or recreational, associated with leisure and 'fun in the sun' (O'Neill et al., 2023). Such imagery can unintentionally downplay the seriousness of extreme heat and weaken risk perception. Presenting heat risk in ways that accurately reflect its health, livelihood, and infrastructure impacts, rather than recreational imagery, is therefore essential.

Making risk knowledge accessible

Producing risk information is not sufficient; it must be accessible, understandable, and usable by a diverse range of users. This includes translating complex information into local languages, visual formats, and tools such as risk or vulnerability maps that communities and authorities can use to target action. It also requires careful attention to the terminology used to describe heat risk. Across countries, a wide range of technical terms and indices are used (e.g. Heat Index, heat dome, heat alert/watch/advisory), which can create confusion and reduce trust if there is no clear explanation.

Making risk knowledge accessible and usable is a shared responsibility across institutions. Effective heat risk assessments depend on collaboration and data sharing between meteorological services, health authorities, disaster risk management agencies, statistical offices, and sectoral actors. However, in many countries, both meteorological and impact data remain fragmented, restricted, or unavailable, which limits the development of integrated and locally relevant heat risk profiles. This can constrain the ability to identify vulnerable groups, develop impact-based thresholds, and translate risk knowledge into actionable guidance.

In addition, heat risk information is not always tested or co-developed with intended users. Without engagement with local authorities, sectoral decision makers, and communities, technically robust products may be difficult to interpret or apply in practice. Co-production processes and the integration of scientific, local, and experiential heat risk knowledge can improve clarity, relevance, and uptake, ensuring that this knowledge effectively informs warning design, preparedness, and anticipatory action.

Pillar 1 gaps and challenges

Despite widespread evidence that extreme heat is already a major and growing risk in most regions of the world, many countries still lack up-to-date, locally specific heat risk assessments. Data limitations remain a major constraint. In many settings, meteorological, health, and socio-economic data are fragmented, restricted, or inconsistently collected, while surveillance systems for heat-related impacts are weak or incomplete. Inconsistent definitions of extreme heat and unclear institutional mandates further hinder the development of coherent and integrated risk knowledge. Health and mortality records are often insufficiently disaggregated by gender, socio-economic status, occupation, housing conditions, and urban–rural differences, limiting the ability to identify vulnerability pathways and design targeted and equitable interventions. In addition, patterns such as urban expansion, ageing populations, gender inequality and social exclusion, migration, informal housing, and changing labour patterns continually reshape risk. Risk is dynamic and changes over time, yet many assessments rely on static or outdated datasets that may fail to capture where risk is really felt. Strengthening interoperable, disaggregated, and regularly updated data systems, alongside qualitative and participatory approaches, is therefore essential.

Important knowledge gaps also persist across sectors. While heat-health research has expanded significantly in many countries, exposure and vulnerability assessments remain uneven across regions and population groups. A recent review found that only a small proportion of studies on heat adopt comprehensive risk frameworks and that research remains heavily concentrated on health, with far less attention given to infrastructure, agriculture, ecosystems, energy and food systems, and other societal systems (Brogno et al., 2025). This imbalance constrains holistic, cross-sectoral risk assessments and the development of effective preparedness and early action. An equity perspective is also critical to understand how structural inequalities and differential exposures shape impacts.

There are also many gaps in understanding heat risk perception across communities, stakeholders, and decision makers, especially in lower- to middle-income countries: the only global review on heat risk perception, to date, reviewed 31 studies from 2010 to 2020 and found that most studies were from the USA, China, and Australia, mostly in urban settings (Hass et al., 2021; Figure 8). While more studies have been done since 2020, including eight studies in lower- and middle-income countries supported through a small-grant initiative led by the Global Disaster Preparedness Center of the American Red Cross, the Red Cross Red Crescent Climate Centre, and the Global Heat Health Information Network (GHHIN), the overall evidence base remains geographically and socio-economically uneven.

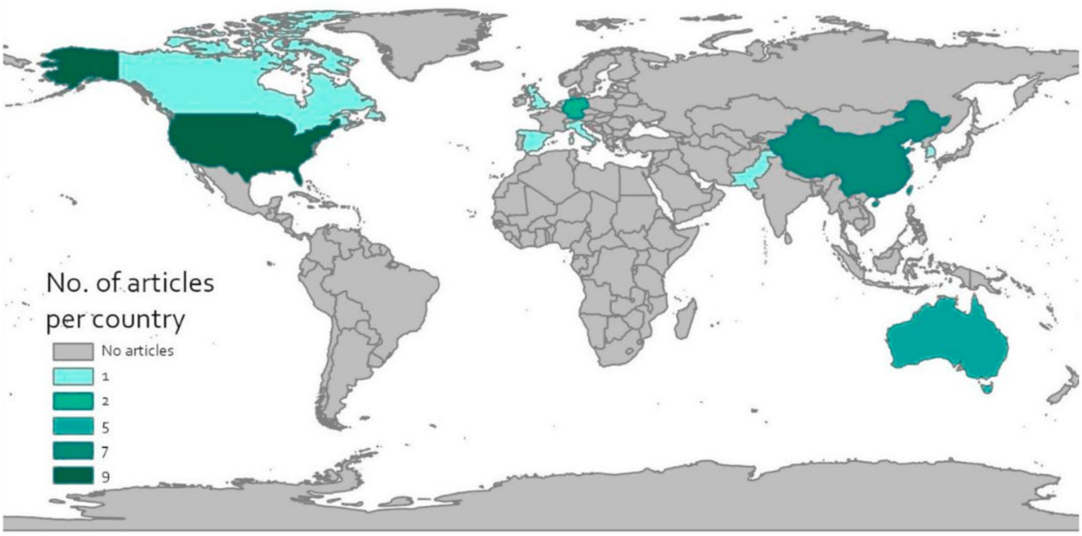

Figure 8 Study locations of heat risk perception studies from 2010 to 2020. Source: Hass et al. (2021)

Finally, a persistent science–practice gap limits the operational use of heat risk knowledge. Even where robust evidence exists, it does not always translate into warning thresholds, preparedness planning, and sectoral action. Strengthening co-production, institutional coordination, and knowledge-sharing mechanisms can help ensure that risk information is relevant, trusted, and embedded in decision-making processes.

Pillar 2: Observations, monitoring, analysis, and forecasting

How do we detect, monitor, and forecast hazardous heat in time to trigger early action? Pillar 2 forms the technological backbone of HEWSs. It ensures that countries can detect hazardous heat, monitor evolving conditions, and generate reliable forecasts with sufficient lead time to trigger early action. This includes maintaining observation networks, analysing climate and environmental data, and developing impact-relevant heat forecasting products that inform decision-making across sectors.

NMHSs are central to this pillar, operating monitoring systems, issuing warnings, and translating meteorological information into actionable services. Their work is supported by global and regional data-sharing, modelling, and forecasting frameworks coordinated by the WMO. Within the EW4All initiative, Pillar 2 is globally led by the WMO, reflecting its mandate to strengthen observation systems, forecasting capacity, and international collaboration to improve early warning coverage and reliability worldwide (Egerton et al., 2022).

Observations and monitoring

Reliable observations are the foundation of heat monitoring and forecasting. Ground stations, satellites, and upper-air measurements provide the real-time data for weather prediction models. Many low- and middle-income countries still face sparse station networks, limited maintenance, and inconsistent data sharing, reducing the accuracy of both global and national forecasts. For heat specifically, temperature is widely monitored, but additional variables such as humidity, wind speed, and solar radiation are needed to calculate thermal stress indices. In some countries, these parameters are not consistently observed or lack long-term records, limiting both climatological analysis and the operational use of more complex indices. Under the EW4All campaign, the Systematic Observations Financing Facility (SOFF) initiative was launched in July 2022 with the aim of strengthening weather observational systems (SOFF, 2023). The first country funding was approved in March 2023, and today 60 countries are receiving initial SOFF support.

Although heatwaves are large-scale meteorological phenomena, exposure is strongly shaped by local conditions. Official weather stations follow standardized siting guidelines and are often located outside dense urban areas, meaning that they may underestimate temperatures in cities (World Meteorological Organization, 2021). UHIs, building materials, and limited ventilation can significantly amplify heat at the neighbourhood scale. Indoor exposure adds another layer of complexity, as internal temperatures can be higher than outside, buildings can retain heat for days after outdoor temperatures go down, and internal temperatures can vary strongly between building type, floor, and other factors (Tham et al., 2020; Correia et al., 2025; Peerlings and Steeneveld, 2025). Yet systematic urban and indoor monitoring remains limited, and many fine-scale datasets stemming from short-term research projects are limited by challenges around calibration, continuity, and institutional ownership, constraining their sustained use in forecasting and warning systems. Strengthening collaboration between meteorological institutes, cities, and research institutions can help improve long-term monitoring.

Forecasting skill and lead time

Modern weather forecasting underpins all HEWSs. Most countries rely on global forecasting models, typically with a spatial resolution of around 9–13 km, which simulate the atmosphere using large volumes of observational data. While this scale is sufficient to capture large-scale weather patterns and temperature anomalies, it does not fully resolve local features such as UHIs, complex terrain, or coastal gradients that strongly influence heat exposure. While some countries operate higher-resolution regional models (e.g. 1–4 km), these are typically available only for short lead times of a few days and require substantial computational resources, technical expertise, and sustained investment. As a result, such capabilities are more common in higher-income countries, while many low- and lower-middle-income countries rely primarily on global models and external forecast products.

In practice, both modelling approaches are complementary. Global models provide longer lead times and early situational awareness, while regional models support more localized and spatially detailed information closer to the event. Forecast outputs from multiple models are typically interpreted and combined with weather observations and expert judgement by meteorologists before warnings are issued. Even with high-resolution models, neighbourhood-scale variability and microclimates remain difficult to capture. Therefore, context-specific interpretation and the expert judgement of meteorologists remain crucial.

Forecast skill has improved substantially: today's six-day general weather forecast is as accurate as a five-day forecast a decade ago (Bauer et al., 2015). Temperature, in particular, is one of the most predictable weather variables, often with useful skill at lead times of three to 10 days, providing a strong foundation for anticipatory action (De Perez, 2018; McGregor, 2024). However, forecast performance varies by region. Skill tends to be stronger in the extra-tropics and weaker in parts of Africa, the Maritime Continent, mountainous regions, and some small island states, where localized climates and limited observational data reduce model performance (De Perez, 2018). Humidity and wind are less predictable compared to temperature, reducing forecast reliability for these variables. AI-driven weather forecasting models are also rapidly emerging (see Artificial intelligence and HEWSs on page 48).

Beyond short-term forecasts (three to five days ahead), sub-seasonal (two to four weeks) and seasonal (one to three months) outlooks can provide early indications of elevated heat risk at longer timescales. While these forecasts are typically expressed as likelihoods of above-normal temperatures rather than specific temperature values or events, and are therefore less precise, they can support preparedness measures such as planning staffing, strengthening public awareness campaigns, pre-positioning resources, and preparing health and energy systems. For example, since 2017, the Caribbean Climate Outlook Forum has provided seasonal heat outlooks, estimating the likelihood of exceeding thresholds for hot days during the heat season, which supports anticipatory planning at regional and national levels (The Climate Studies Group Mona and The University of the West Indies, 2020).

Selecting heat metrics for early warnings

Weather forecasts provide the raw meteorological ingredients used to issue heat warnings. These variables may be used directly (e.g. daily maximum and/or minimum temperature) or combined to calculate heat stress indices (Pereira Marghidan et al., 2025). The choice of metric matters: it shapes how heat is detected, how early you can detect it with accuracy, which areas are identified as most at risk, and which impacts it may best relate to (Pereira Marghidan et al., 2025). Different climates, populations, and sectors may require different metrics to capture heat. For example, humidity may be more important in tropical climates, while air temperature may better explain impacts in temperate regions. Similarly, sectors such as health, labour, agriculture, or energy may have different sensitivities and decision needs regarding how heat is measured.

Hundreds of metrics have been developed to research, detect, and characterize extreme heat (Pereira Marghidan et al., 2025). A smaller subset of metrics is used in operational HEWSs, as these must rely on forecastable variables and must be feasible to compute. Different heat metrics capture different aspects of heat. For example, Figure 9 shows that the most extreme conditions identified by different heat metrics do not fully overlap spatially, illustrating how they capture different dimensions of heat (Cvijanovic et al., 2023).

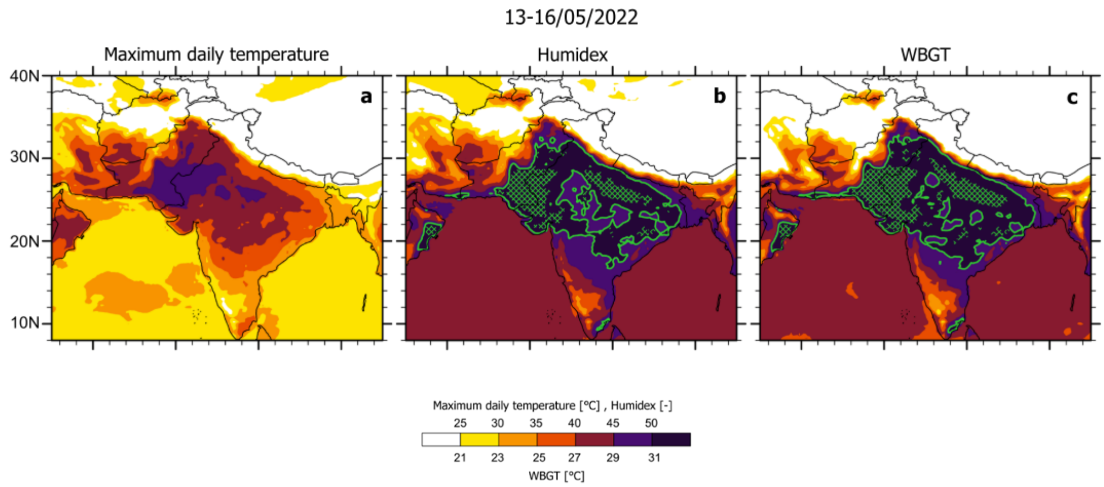

Figure 9 Maximum daily temperature (°C), humidex (unitless), and WBGT on 13 May 2022, during the May Pakistan–India heatwave. Green contours indicate areas that exceeded dangerous heat-stress thresholds (humidex >50 and indoor WBGT >31°C), while green stippling marks regions with even more extreme conditions (humidex >54 and WBGT >33°C). The figure shows that the most extreme conditions identified by each index do not fully overlap spatially, illustrating how different heat indicators capture different dimensions of hazardous heat. Source: Cvijanovic et al. (2023)

Heat metrics for early warnings vary in complexity and in the type of information they require. Simple meteorological variables such as temperature are direct outputs of weather forecast models, making them straightforward to monitor, forecast, and communicate. Indices such as the HI require additional calculations based on forecast temperature and humidity. More complex physiological metrics, such as the WBGT, require multiple inputs (temperature, humidity, wind speed, radiation) and additional modelling steps. As indicators become more complex, uncertainty increases because each variable introduces additional forecast error. This can shorten reliable lead times and complicate the warning process, particularly in data-scarce settings. Globally, warning systems use a wide range of metrics. The WMO/WHO group these broadly into 1) temperature-based indicators, 2) thermal stress indices, and 3) heatwave intensity indices that capture cumulative heat load over multiple days.

Countries may choose a certain heat metric depending on factors such as the climatic context, available data and computational power, institutional preferences, simplicity, available resources, what neighbouring countries are doing, or, in some cases, the link with health evidence (Pereira Marghidan et al., 2025).

Most countries rely on **maximum temperature-**based thresholds because they are simple and forecastable, with relatively longer lead times (e.g. Azerbaijan, Croatia, Czech Republic, Greece, India, Kazakhstan, Latvia, Malta, Mozambique, Netherlands, Pakistan, Portugal) (Kotharkar and Ghosh, 2022; McGregor, 2024) (Figure 10). Others include **minimum temperature** or **both maximum/minimum temperature** to capture the occurrence of warm nights (e.g. Belgium, Canada, France, Hungary, Poland, Spain). Some countries use **thermal stress indices**, including apparent temperature (Italy), perceived temperature (Germany),[2] humidex (Canada), HI (Curaçao, Philippines, Senegal, USA), or WBGT (Japan, Singapore). Australia uses a **heatwave intensity metric** (the Excess Heat Factor), which is based on both the maximum/minimum temperature and also accounts for

[2] Apparent temperature generally refers to simplified formulations that combine air temperature and humidity to estimate heat, whereas perceived temperature is derived from more comprehensive human heat-balance models that also account for radiation, wind, and physiological responses.

short-term acclimatization, but which gives an intensity measure. A smaller group of countries use air mass-based or synoptic approaches (McGregor, 2024). This method, first developed in the 1990s in Philadelphia, USA, identifies 'dangerous' air masses defined by a combination of weather factors that occur together over several days. Instead of relying on one threshold, it classifies air masses (e.g. hot, humid maritime tropical air) and issues different warning levels depending on their likelihood and expected mortality impacts. Although it was one of the first truly impact-based systems and spread to several countries (e.g. in the US, Italy, China, Canada), the approach remains uncommon today. Its complexity, dependence on many forecast variables, and need for location-specific calibration make it difficult to operate compared to simpler temperature-based or heat-index thresholds.

Meteorological parameters and system elements for triggering heat-related warnings.

Country	Meteorological Parameter/Indices	System Elements[2] Threshold based on historical mortality	Excess mortality forecast	Duration of heat wave event	Seasonality of adaptation	Regionally variable thresholds	Human expertise
Australia (Queensland)	AT			2 days		✓	✓
Austria	PT	✓		✓		✓	✓
Azerbaijan	T_{max}						✓
Belarus	T			✓	✓		
Belgium	T_{max}/T_{min}/Ozone			3 days			
Canada (Montreal)	T_{max}/T_{min}			✓			
Canada (Toronto region)	Airmass	✓	✓	✓	✓	✓	✓
Canada (other regions)	Humidex			✓			
China (Hong Kong)	NET	✓		✓			✓
China (Shanghai)	Airmass	✓	✓	✓	✓		✓
Croatia	T_{max}						
Czech Republic	T_{max}			✓			✓
France	T_{max}/T_{min}	✓		3 days		✓	✓
Germany	PT			2 days	✓	✓	✓
Greece	T_{max}			✓		✓	
Hungary (Budapest)	T_{mean}	✓					
India	T_{max}			2 days		✓	✓
Italy	Airmass/AT	✓	✓	✓	✓	✓	
Japan	WBGT	✓	✓	✓		✓	✓
Kazakhstan	T			✓		✓	
Latvia	T_{max}			✓			
Luxembourg	PET			✓			✓
Malta	T_{max}			✓			✓
Netherlands	T_{max}			✓			
Pakistan	T_{max}			2 days		✓	✓
Poland	T_{max}/T_{min}			✓			
Portugal	T_{max}	✓	✓	✓		✓	✓
Republic of Korea	Airmass	✓	✓	✓	✓	✓	✓
Republic of Korea (Seoul)	Airmass	✓	✓	✓	✓	✓	✓
Romania	ITU	✓		✓			
Serbia and Montenegro	T_{max}/T_{min}			✓			
Slovenia	Forecaster					✓	✓
Spain	T_{max}/T_{min}	✓				✓	✓
Switzerland	HI						
Turkey	ITU			✓			
UK (England & Wales)	T_{max}/T_{min}			✓		✓	
US (synoptic)	Airmass	✓	✓	✓	✓	✓	✓
US (others)	HI			2 days		✓	✓
Yugoslav Republic of Macedonia	ITU			✓		✓	✓

where, T: temperature; T_{max}: maximum temperature; ET: equivalent temperature; T_{min}: minimum temperature; T_{mean}: mean temperature; HI: heat index; HD: humidex; AT: apparent temperature; PT: perceived temperature; NET: net effective temperature; ITU: temperature humidity index

(*Source:* *Kent et al., 2002*; *Kirchmayer et al., 2004*; *WHO, 2004*; *Nogueira, 2005*; *Nationaal Hitteplan, 2007*; *Nicholls et al., 2008*; *DHS, 2009*; *WHO, 2009*; *Hajat et al., 2010*; *Martinez et al., 2011*; *WHO, 2011b*; *Lowe et al., 2011*, *2016*; *Chebana et al., 2012*; *Laaidi et al., 2013*; *Åström et al., 2014*; *Culqui et al., 2014*; *WMO & WHO, 2015*; *Matzarakis, 2016*; *Karachi Heatwave Management Plan, 2017*; *MoH, 2018*; *PHE, 2018*; *Price et al., 2018*; *Casanueva et al., 2019*; *NDMA, 2019*; *Basarin et al., 2020*; *Chae & Park, 2021*; *Pascal et al., 2021*).

[2] System elements indicate different aspects of heat-health warnings based on spatial and temporal variations, expertise, time and duration of heat event and resource availability. The countries which exhibit different elements are given a tick mark (✓) while the others are left blank.

Figure 10 System elements for triggering heat-related warnings around the globe. Source: Kotharkar and Ghosh (2022: 14)

Over time, countries have also refined and updated the heat metrics underpinning their systems as scientific evidence has evolved. For example, Japan went from using temperature to the WBGT index after epidemiological evidence in 2020 (Oka et al., 2023), and Switzerland shifted from using the Heat Index to mean daily temperature in 2021 (Burgstall et al., 2019), both due to new scientific evidence comparing different indices with mortality risks. The Netherlands shifted from using combined maximum and minimum temperature thresholds to relying solely on a maximum temperature trigger in order to improve operational simplicity (Pereira Marghidan, 2026). In some cases, existing warning systems were expanded to serve multiple audiences. For example, Portugal's initial HHWS (ÍCARO) targeted public health (Leite et al., 2020), while the meteorological service later also introduced warnings based on extreme temperature thresholds.

Much of the research on heat metrics to underpin HEWSs comes from epidemiological studies that seek to identify which indicators and heat definitions are most strongly associated with mortality. However, these studies do not provide clear or consistent answers on which metric best explains heat-related mortality across different regions. Evidence shows that the best-performing heat metric for predicting mortality differs by country, even in similar climates (Lo et al., 2023; Pereira Marghidan et al., 2025). More complex indices also do not consistently outperform temperature alone for predicting mortality (Pereira Marghidan et al., 2025). In addition, humidity-based metrics may be more relevant in regions where high temperatures are not always accompanied by high humidity (Pereira Marghidan et al., 2025).

Overall, selecting heat metrics involves important trade-offs. No single indicator performs best in all settings, and choices must balance scientific relevance, forecast skill, feasibility, and usability. There is no universal 'best' metric. The most appropriate indicator depends on the decision context, available data and forecasting capacity, and the populations and sectors the system aims to protect. Transparency in how thresholds are defined is essential to build trust and enable evaluation. Local validation ensures that indicators are meaningfully linked to observed impacts in a specific setting, while operational feasibility determines whether systems can be sustained over time. Alignment with user needs and institutional mandates is also critical, as different sectors may require different lead times, spatial scales, and levels of complexity.

At the same time, systematic evidence comparing the performance of different indicators across climatic and sectoral contexts remains limited. Developing clearer guidance on context-specific metric selection is an important research priority. In this context, the forthcoming WMO–WHO *Handbook of Extreme Heat Indicators, Indexes and Metrics: A Measurement Guide for Characterizing and Monitoring Heatwaves for Impact Services*, expected in 2026, aims to support countries by summarizing commonly used heat metrics and their respective strengths, limitations, and operational considerations.

Setting thresholds for heat warnings

Thresholds determine when forecasts translate into alerts and therefore shape warning frequency, credibility, and impact relevance. Countries adopt different approaches. Absolute thresholds use fixed values (e.g. a specific temperature sustained for several days), while relative thresholds are based on local climatology (e.g. exceeding the 95th percentile over a selected, usually 30-year, reference period). Absolute thresholds offer operational simplicity and ease of communication, while relative thresholds better reflect what is unusual for a specific climate. However, how unusual or rare a heat event is compared to the local climate does not always directly reflect how severe its impacts will be on people or society.

Thresholds may be derived from climatological statistics or based on impacts; for example, they may be based on epidemiological analyses linking temperature to mortality or experiential knowledge of when impacts begin to occur. Epidemiologically derived thresholds offer a clearer link to health protection but require reliable health data. Japan provides a strong example of this approach (see Box 1; Guo et al. 2024; Phung et al., 2025), where WBGT-based thresholds were reassessed using district-level mortality data, leading to evidence that lower and regionally adjusted trigger levels could substantially increase the proportion of preventable heat-related deaths.

In most countries, thresholds are fixed throughout the season, but in a few cases, thresholds are adjusted by month, as early-season heat can be particularly harmful as populations are less acclimatized. Studies have shown that, for example in Quebec, Canada, seasonally adjusted thresholds can improve mortality prevention while maintaining manageable false-alarm rates (Issa et al., 2021). Similarly, Italy applies dynamic thresholds that vary by month, with differences of up to around 10°C between early and late summer. Such dynamic thresholds may be particularly relevant for health outcomes and may not always align with impacts across other sectors.

The spatial scale of thresholds is a critical consideration. Some countries use one single threshold for the whole country, which promotes clarity and consistency but may mask regional climate differences and uneven vulnerability patterns. Regional or city-level thresholds improve local relevance and will be necessary in larger countries or countries with diverse climates, but they increase operational complexity.

Furthermore, where feasible, thresholds require periodic reassessment – for example, every five years – to account for rising temperatures, shifting baseline climates, demographic change, urbanization, and evolving vulnerability patterns. Without regular review, thresholds risk becoming misaligned with current risk levels (Hess and Ebi, 2016).

Overall, most national EWSs issue population-level warnings that reflect an average level of risk (O'Connor et al., 2025). Yet heat risk is unevenly distributed, shaped by factors such as age, gender, occupation, housing quality, urban heat island exposure, and access to cooling and healthcare. Certain vulnerable groups may experience harmful impacts at lower temperatures and therefore require earlier protective action than the general population. Lowering thresholds uniformly, however, may lead to frequent alerts that are not as relevant for other groups, potentially undermining trust and compliance. Pairing broad public alerts with more targeted, vulnerability-informed warning and outreach mechanisms, including sector-specific or individualized approaches (see Impact-based forecasting for heat on page 45), can more effectively extend protection to those most at risk (O'Connor et al., 2025).

Monitoring emerging impacts and proxy indicators

Monitoring impacts can complement meteorological monitoring of heat by providing more context-specific signals of dangerous heat. Health surveillance systems, such as real-time monitoring of emergency department visits, ambulance dispatches, syndromic indicators, or mortality, are used in some systems to help validate and adjust warning thresholds and action in real time, such as is done in France (Pascal et al., 2012).

In countries where timely near-real-time health data are not available, proxy near-real-time indicators such as social media activity, internet search trends, and media attention can provide rapid insights into population stress, risk perception, and behavioural responses during heat warnings. Studies in Australia, Italy, the UK, and the USA found that the daily volume of heat-related tweets was significantly associated with extreme temperatures, and tweet activity also followed the spatial and temporal patterns of heatwaves (Grasso et al., 2017; Youn et al., 2021). Furthermore, research in India found that heat-related tweets correlated with heat-related mortality better than several climate-based heatwave indicators and helped identify dangerous events that did not always emerge clearly in temperature-only definitions (Cecinati et al., 2019).

These approaches may therefore support real-time situational awareness, particularly in data-scarce contexts where health data are delayed, incomplete, or unavailable. Despite growing research, these approaches are still rarely used in operational HEWSs. Integrating health and proxy monitoring within HEWSs can strengthen early detection, improve targeting of interventions, and enhance post-event learning and evaluation.

Box 1: Updating WBGT-based heat warnings in Japan based on health evidence

Japan's heat-warning system has evolved significantly over recent years. Prior to 2021, warnings were issued under the Hot Temperature Alert, based on a daily maximum temperature of 35˚C. Recognizing the limitations of using air temperature alone, the Japan Meteorological Agency and the Ministry of the Environment introduced the Heatstroke Alert system, which issues alerts when the WBGT exceeds 33˚C, and 'special alerts' when the WBGT is higher or equal to 35˚C (Figure 11).

Earlier research (Lo et al., 2023) confirmed that the WBGT outperforms temperature indicators such as T_{max} in predicting heat-related morbidity, particularly for all-cause, non-external, and heat-stroke cases, supporting its adoption as Japan's core heat-warning metric. However, its relationship with mortality remained less well established. To address this, recent research by Phung et al. (2025) analysed daily heat-stroke deaths (2010–19) across all 47 districts to identify thresholds that could better mitigate preventable mortality. Their findings showed that the current Heatstroke Alert (HA2021) system threshold (WBGT = 33˚C) would prevent only 2–3% of heat-related deaths, whereas an optimized threshold of WBGT around 31˚C could prevent up to 50% of heat-related deaths nationwide.

Lower thresholds were found to be needed in **northern or cooler regions** and during early summer, when populations are less acclimatized to heat. Mortality risk was particularly high among **older adults** and, in some regions, **men**, underscoring the importance of tailoring warnings and preparedness measures to vulnerable groups.

Together, these studies provide strong epidemiological evidence that data-driven, regionally calibrated WBGT thresholds can improve Japan's heat-warning effectiveness and better align the system with national health protection goals under a warming climate.

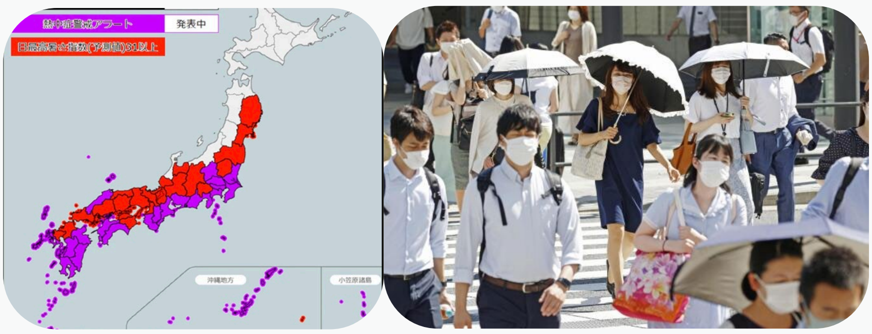

Figure 11 Alert levels in Japan. Photo: Yusuke Ogata/AP. Source: Guo et al. 2024; Phung et al., 2025

Pillar 2 gaps and challenges

Despite advances in the observation, monitoring, analysis, and forecasting of heat, important gaps remain. Observational networks are uneven, particularly in lower-income countries, limiting forecast accuracy and the use of more complex heat indices. Regions with highly heterogeneous landscapes (such as coastlines, urban areas, and mountainous terrain) and small island states face additional challenges in heat monitoring and forecasting. Local-scale processes, including land–sea interactions, urban heat islands, and elevation differences, are often not well captured by models, which can lead to biases or underestimation of heat, while sparse observational networks further limit validation and refinement of forecasts. Urban and indoor heat is rarely monitored systematically over the long term, creating blind spots in understanding heat where it is actually felt. Metric selection and threshold-setting approaches for heat remain fragmented around the world, and these require reassessment under climatic and population-level changes. Public-facing warnings rely on population-level thresholds that inherently do not account for differences in risk between populations and sectors.

In most countries, the NMHS provides the authoritative hazard information and population-level warning, indicating when heat becomes dangerous and triggering cross-sectoral readiness. These warnings sit within a broader suite of extreme heat services, which may include specific heat indices (e.g. Universal Thermal Climate Index, WBGT), hazard climatologies, future climate scenarios, and seasonal forecasts. Together, these products support sectors in tailoring preparedness and operational decisions. However, due to persistent gaps in the availability and use of heat risk information, monitoring, forecasts, and decision-support products, a growing number of non-NMHS actors (e.g. NGOs, humanitarian organizations, and the private sector) have begun developing complementary heat-related monitoring tools and services. This trend is driven in part by the absence of clear operational guidance and shared standards for extreme heat, as well as ongoing capacity and resource constraints in many contexts.

Ideally, NMHSs should remain the authoritative source of heat hazard information and associated services, ensuring scientific rigour, consistency, and alignment with international standards such as those promoted by the WMO. At the same time, these complementary efforts can play an important role in expanding coverage, fostering innovation, and accelerating impact-oriented approaches while national systems evolve. However, without effective coordination and long-term institutional anchoring, parallel initiatives may risk fragmentation, inconsistent messaging, or limited sustainability. Strengthening collaboration, clarifying roles, and aligning services can help ensure that these efforts reinforce rather than undermine national EWSs.

Overall, strengthening this pillar requires sustained investment in observations, clearer guidance on heat metric and threshold selection, regular review processes, and stronger integration between forecasts and impact data to ensure warnings are relevant, useful, actionable, and equitable.

Pillar 3: Warning dissemination and communication

How do we ensure that heat warnings reach people in time and in a form they can act on? Pillar 3 focuses on how heat warnings and risk information are delivered to people and institutions who need to act on them. Even the most accurate forecast reduces impacts only if it reaches the right audiences, is trusted, understood, and prompts timely action. Dissemination is about how warnings reach users, and communication is about what is said and how it is framed.

At the national level, this pillar is typically coordinated by disaster risk management or civil protection authorities, in collaboration with communication agencies, telecommunication regulators, mobile network operators, media organizations, and, increasingly, private sector and community-based organizations. While NMHSs often issue the technical warning, effective dissemination requires strong partnerships beyond the meteorological community. Within the EW4All initiative, this pillar is globally coordinated by the International Telecommunication Union, reflecting its mandate to strengthen institutional mandates, communication infrastructure, and digital connectivity, and to ensure quality and trust.

Dissemination: reaching people through trusted channels

Dissemination refers to how warnings reach users. As with all warnings, dissemination must be multichannel and inclusive. Mass media (radio, television) remain critical for broad public reach, particularly in lower-resource settings. Digital tools such as SMS alerts, cell broadcasts, push notifications, and social media enable rapid and targeted outreach. Effective systems therefore combine national alerts with 'first-mile' dissemination through trusted intermediaries and directly to people at risk: community health workers, Red Cross volunteers, pharmacies, religious institutions, local radio, schools and learning spaces, and neighbourhood networks (GHHIN, 2023a). In some contexts, phone services (e.g. TeleCross in Australia) or consultation hours (e.g. Amsterdam's weekly heat consultation hour) provide additional support. The Common Alerting Protocol[3] can strengthen coordination by enabling standardized alerts to be distributed simultaneously across platforms, reducing inconsistencies and delays. As with all hazards, it is crucial to diversify warning channels and build in high- and low-tech redundancies in the system: for example, power outages during heatwaves may disrupt digital communication channels.

Why heat communication is uniquely challenging

Heat presents unique communication challenges compared to other hazards. Unlike floods, storms, or wildfires, heat is largely invisible. Media narratives frequently portray heat as positive ('fun in the sun') (O'Neill et al., 2023). In hot climates especially, people may underestimate the danger or believe they are accustomed to high temperatures (GHHIN, 2023a). Many individuals fail to recognize early symptoms of heat stress or misjudge their personal vulnerability (Arrighi et al., 2025).

Figure 12 Heat messaging. Source: Syed et al. (2022)

Guidance for journalists developed by the GHHIN emphasizes the need to portray heat accurately by focusing on health

[3] The Common Alerting Protocol is an international standard for formatting and exchanging emergency alerts across different communication systems. For more information, see https://wmo.int/activities/common-alerting-protocol-cap.

Figure 13 'Heatwave Robot': art by Andrew Rae and Ruskin Kyle. Source: https://www.flickr.com/photos/climatecentre/albums/72177720317682475/

impacts, night-time heat, strain on services, and disproportionate risks for vulnerable groups rather than recreational imagery (GHHIN, 2023b). To address the visual challenges, the GHHIN, in partnership with Internews' Earth Journalism Network (EJN), launched a global extreme heat photo contest in 2025.[4] The initiative aimed to make the impacts of extreme heat more visible and relatable by documenting how heat affects daily life, livelihoods, and communities around the world.

At the same time, heat is often predictable several days in advance and may persist for multiple days. This creates important opportunities for phased and proactive communication, allowing authorities to gradually raise awareness, activate preparedness measures, and mobilize resources well in advance, which is often not possible for other rapid-onset hazards. However, this longer lead time can also reduce perceived urgency. Repeated or prolonged warnings may lead to complacency, message fatigue, or declining attention, particularly when impacts are not immediately visible. Maintaining engagement over several days, while clearly communicating evolving risk and required actions, remains a key challenge. In practice, public warnings are often issued closer to the event to ensure high forecast certainty, sometimes even bound by legal constraints in lead time. However, when confidence in forecasts is already high several days in advance, earlier communication may provide important preparedness benefits for both the public and key sectors. This raises important questions about how to balance timeliness, certainty, and user needs (GHHIN, 2023a).

Message content: from weather to impact and action

Research consistently shows that simply reporting temperatures is insufficient, and messages are most effective when referring to expected impacts and clear behavioural guidance (Vandermolen et al., 2022; Heidenreich, 2024). Effective heat communication translates meteorological information into impacts and actions. Studies from the USA demonstrate that common technical terms such as 'heat index', 'excessive heat watch', or 'heat advisory' are often misunderstood (Olson & Sutton, 2025; Olson et al., 2023). Nearly half of surveyed participants believed the Heat Index simply meant air temperature, and very few mentioned humidity as a contributing factor. This highlights the importance of using plain language and explicitly explaining what makes heat dangerous (e.g. humidity, night-time temperatures, duration), rather than assuming technical labels are self-explanatory.

Research from the UK further shows that colour-coded systems ('amber', 'red') and terms like 'heatwave' do not automatically signal seriousness (Tang, 2022). What most strongly increases perceived urgency is explicit reference to impacts, such as health consequences, strain on services, or risks to vulnerable groups. Warnings are interpreted through prior experiences and trust in institutions; terminology alone does not convey risk.

[4] For more information, see https://heathealth.info/extreme-heat-photo-contest/.

Media guidance also stresses that reporting should highlight cascading and systemic effects – including electricity demand, labour disruption, and health service strain – and should link risk information to available support measures such as cooling centres or community outreach (GHHIN, 2023b).

Designing messages rooted in behavioural science

Actionable heat communication should go beyond generic advice and should draw from behavioural science and physiological evidence (McLoughlin et al., 2023). Research shows that awareness alone is insufficient: messages are more effective when they combine information on the severity of the heat (e.g. 'even healthy adults can experience heat-stroke'), explain why protective actions are effective (e.g. 'cooling down and hydrating significantly reduce heat-related illness'), reduce perceived costs or barriers to acting, and explain how it might impact certain groups differently. Communication should therefore strengthen both risk appraisal and confidence in protective actions.

At the same time, communication must avoid placing the burden solely on individuals. Advising low-income households to 'find a cool location' overlooks economic and social realities and can undermine trust if the advice does not match people's lived constraints (Arrighi et al., 2025). Effective communication acknowledges structural barriers, clarifies available public support (e.g. cooling centres, extended service hours, volunteer check-ins), and promotes shared responsibility between authorities, communities, and individuals.

A guidance note on heat communication for cities in South Asia states that effective heat communication requires dedicated heat communication plans, aligned triggers between meteorological and health agencies, pre-developed message templates, and tailored outreach to high-risk groups (Sen et al., 2022). It also stresses the importance of sustained, season-long communication rather than one-off alerts during extreme events.

Building heat literacy before warnings: seasonal awareness and sustained communication

Warning messages are most effective when they build on a foundation of broader risk education. Regular, season-long communication, through awareness campaigns, trainings, simulations, workplaces, and school curricula, helps people recognize heat illness early, understand who is at risk, and internalize practical actions. This 'heat literacy' increases trust and reduces the cognitive burden during an event, so warnings act as a prompt to implement familiar protective behaviours rather than introducing new information under time pressure.

Where this broader heat risk education is lacking, warning messages may be misunderstood, ignored, or interpreted as routine weather information. For example, people may not recognize early symptoms of heat stress, may underestimate their personal risk, or may not know what protective actions are feasible in their context. This can delay response, increase health impacts, and place greater strain on emergency and health services during extreme events.

Heat communication should not be limited to episodic warning messaging. Sustained seasonal outreach, public awareness campaigns (e.g. Heat Action Day on 2 June[5]), and media engagement before peak heat periods help build shared understanding and social norms around protective behaviours. In chronically hot regions, continuous engagement may be more appropriate, while in temperate climates, seasonal 'refreshers' and having a clear 'heat season' (similar to preparedness messaging during hurricane or wildfire seasons) can help maintain preparedness and counter complacency after cooler years.

[5] Heat Action Day on 2 June is a global day for raising awareness of heat risks; see https://www.ifrc.org/get-involved/campaign-us/heat-action-day.

Reaching vulnerable and diverse populations

Heat risk is unevenly distributed. Effective dissemination requires tailored outreach to high-risk groups, including older adults, children, pregnant women, outdoor workers, informal settlement residents, people experiencing homelessness, migrants, and tourists who may be unacclimatized. Collaboration with organizations already working with these groups, such as migrant support services, labour unions, faith-based groups, women's organizations, youth organizations, elderly care providers, or homelessness services, can improve reach and trust. A gender equality and social inclusion (GESI) approach recommends diversifying outreach methods, translating warnings into multiple local languages, using visual formats and accessible materials, and ensuring culturally appropriate communication. This helps bridge information gaps and ensures that those most at risk can receive, understand, and act on warnings.

Figure 14 Heat communication materials could include videos, social media posts, and posters in multiple languages. Source: https://preparecenter.org/toolkit/heat/

Evaluating effectiveness

Effective heat communication requires systematic evaluation. It is important to assess not only whether warnings are issued, but whether they are received, understood, trusted, and acted upon across different population groups. This includes examining which channels reach whom, which formats are preferred, and whether messages are interpreted as intended.

Evaluation can combine rapid post-event surveys, focus groups, hotline data, media monitoring, and analysis of behavioural indicators (e.g. cooling centre attendance, website traffic, health service use). As mentioned above, reviews have revealed mismatches between official alert terminology and public understanding, underscoring the importance of testing messages before and after implementation. In Senegal, a pilot study on heat warnings in Fatick gathered feedback from a range of groups including farmers, leading to the introduction of voice recordings for users with limited literacy.

Ideally, warning messages should be developed together in consultation with the most vulnerable to ensure the messages and communication platforms are suitable and will be successful in reaching the most vulnerable (rather than gathering feedback afterwards). Equity should be a core evaluation lens. Are older adults, pregnant women, children, outdoor workers, migrants, and low-income households receiving and acting on warnings at similar rates? Are language and accessibility barriers limiting uptake? Without disaggregated monitoring, communication gaps can remain invisible.

Towards more targeted and personalized communication

Emerging approaches attempt to complement broad public warnings with more tailored warnings and/or communication strategies (see Towards targeted, personalized HEWSs on page 46). For example, a proof-of-concept study in Australia tested an individualized digital HEWS among older adults living independently (Oberai et al., 2025). Using indoor sensors and personal health information, the system generated tailored alerts and cooling advice. Over 90 per cent of alerts were followed by reported behavioural action, and preparedness improved after one summer. Other initiatives are developing personalized heat stress apps that integrate environmental data with individual risk factors (GHHIN, 2023a). However, such approaches depend on access to reliable data, digital infrastructure, and monitoring systems, which may be limited in many settings. Individualized digital solutions offer significant potential to reduce heat-related risks, but require deliberate efforts to ensure equitable access and inclusive design, as well as complementary non-digital approaches to protect populations without access to digital technologies.

Furthermore, institutions that regularly engage specific groups also provide important entry points for more tailored communication. For example, schools and childcare services can deliver age-appropriate information to children and caregivers, reinforce hydration and cooling behaviours, and adjust schedules during extreme heat. Employers and labour organizations can provide targeted guidance and protective measures for outdoor and informal workers. Primary healthcare providers and elderly care services can identify high-risk individuals and strengthen outreach and follow-up. Social protection systems and community-based organizations can also support targeted communication and anticipatory actions for vulnerable households.

Place-based strategies can further improve targeting by focusing on high-risk environments rather than individuals. For example, heat risk information and protective guidance can be communicated in transport hubs, markets, workplaces, tourist areas, and informal settlements, where exposure may be highest. Visual materials, community media, and local communication channels can help reach groups who may otherwise be excluded.

These examples illustrate that combining population-level alerts with context-appropriate targeted approaches can meaningfully extend protection. Equity, feasibility, and sustainability must remain central. Targeted communication should therefore be seen as a broader process of identifying who is most at risk, understanding local barriers to action, and using trusted and accessible channels to ensure that warnings lead to effective protective behaviour.

Pillar 3 gaps and challenges

Despite growing recognition of the importance of communication, major gaps remain. Messages are often generic, technical, not co-designed with communities, and insufficiently tailored to local vulnerability patterns. Limited monitoring and evaluation means gaps often remain invisible, especially for the most vulnerable.

Low risk perception remains a heat-specific challenge. Heat is gradual and largely invisible, and many people underestimate its severity. Communication cannot rely only on episodic warnings: sustained engagement throughout the ‘heat season’, similarly to the hurricane season, is needed to maintain preparedness. Without ongoing reminders, populations may forget the urgency of heat, reducing the effectiveness of warnings when they are issued.

Dissemination gaps also remain significant. Unequal access to connectivity, literacy and language barriers, and differences in trusted information sources can limit reach and uptake, and multichannel strategies remain essential. Where available, cell broadcasts offer a key advantage by reaching all phones in a geographic area, including tourists, migrants, and undocumented populations, without relying on opt-in registration. However, they must be complemented by low-tech and community-based channels to ensure inclusivity and redundancy, particularly during disruptions.

Extreme heat itself can undermine the infrastructure that underpins communication systems. Rising temperatures increase electricity demand for air conditioning and ventilation, placing pressure on power grids and increasing the risk of outages. When electricity or mobile networks fail, digital warning channels such as apps, SMS, or social media may become unreliable precisely when timely communication is most critical. Redundant communication pathways, including battery-powered radio, community networks, in-person outreach, and pre-established local support systems, are therefore essential to ensure continuity during cascading system disruptions.

Institutional coordination also presents ongoing challenges. Heat alerts and guidance may be issued by multiple actors across different levels of governance, including meteorological services, health authorities, local governments, and media organizations. In some countries, such as the UK, Portugal, and Hungary, separate meteorological and health warnings coexist for extreme heat, reflecting different mandates and target audiences. While this can improve relevance, it requires strong collaboration and aligned triggers to avoid recipients' confusion. Without clear mandates, standard operating procedures, and shared communication protocols, inconsistent timing, terminology, or advice can reduce trust and delay protective action. Strengthening coordination mechanisms, interoperable platforms, and joint communication strategies across sectors is therefore critical.

Another barrier is that heat seasons often coincide with holiday periods in certain regions. During the 2003 heatwave in France, many health professionals, social workers, and informal caregivers, as well as family members and 'people in charge' (e.g. the Minister of Health) were on vacation, while older adults were left alone (Lagadec, 2004). This reduced monitoring and support for vulnerable populations and contributed to delayed recognition of heat illness and increased mortality. This severely affects continuity of care, emergency response capacity, and communication reach during extreme heat. Warning systems and heat action plans should therefore anticipate seasonal staffing gaps, ensure back-up arrangements, and strengthen community-based support networks during peak heat periods.

Finally, structural and social barriers continue to limit the effectiveness of communication. Even when warnings are received and understood, individuals may lack the resources, time, autonomy, or social support to act. For example, outdoor workers may be unable to modify working hours, low-income households may lack access to cooling, and socially isolated individuals may depend on others for assistance. This highlights that effective communication alone is insufficient. Heat warnings must be linked to structured, equitable preparedness and early action measures, such as social protection, labour regulations, outreach, and access to cooling, which are further addressed under Pillar 4. Strengthening the interface between communication and operational response is therefore essential to ensure that warnings translate into protection, particularly for those least able to act independently.

Figure 15 A young girl in Place Bellecour, Lyon, France in 28°C heat (from the GHHIN-EJN Extreme Heat Photo Contest 2025). Photo: Christina Coellen

Pillar 4: Preparedness and response capabilities

How do heat warnings translate into real action that protects lives? Pillar 4 focuses on the systems, institutions, and capacities that enable heat warnings to trigger timely and effective protective measures. An effective HEWS does not end with issuing an alert; it activates a pre-agreed chain of actions across institutions and communities so that forecast information results in concrete protective measures on the ground.

This pillar is typically led at the national and subnational level by disaster risk management authorities, health agencies, and local governments, often supported by humanitarian partners who help operationalize anticipatory and community-based action. Within the EW4All initiative, Pillar 4 is globally coordinated by the International Federation of Red Cross and Red Crescent Societies, working closely with partners to strengthen preparedness, early action, and community-centred response capacities.

Preparedness and response capacities operate across multiple institutional layers, from government-led planning frameworks to humanitarian anticipatory action mechanisms and local implementation. The sections below outline these complementary approaches.

Heat Action Plans & Heat-Health Action Plans

To institutionalize preparedness and response to heat, countries and cities around the world have developed HAPs or HHAPs. HHAPs refer specifically to health-sector-focused plans, whereas HAPs are used here as a broader umbrella term encompassing multisectoral planning across health, infrastructure, labour, and governance. In practice, both are used interchangeably, and some HAPs include HHAP components within a wider framework.

Originally, these plans emerged as public-health interventions in response to evidence linking extreme heat to excess mortality. Early plans focused primarily on mortality prevention, surveillance, and emergency health responses. The WHO issued the first Heat-Health Action Plan guidance in 2008 (Matthies et al., 2008), identifying eight core components: 1) agreement on a lead body; 2) accurate and timely alert systems; 3) a heat-related health information plan; 4) reduction in indoor heat exposure; 5) particular care for vulnerable population groups; 6) preparedness of the health and social care system; 7) long-term urban planning; and 8) real-time surveillance and evaluation. Over time, however, the scope of these plans expanded to reflect growing recognition that heat is a systemic risk affecting infrastructure, labour, urban environments, and social protection systems. Updated guidance in 2021 further emphasized cross-sectoral coordination, long-term prevention, and integration with climate adaptation and disaster risk reduction frameworks (WHO Regional Office for Europe, 2021). Today, many HAPs/HHAPs integrate short-term emergency response with longer-term adaptation measures such as urban planning.

HAPs/HHAPs typically define alert levels, coordination mechanisms, and responsibilities across actors such as health services, municipalities, emergency responders, labour agencies, utilities, and civil society. In some contexts, national frameworks guide local implementation; in others, cities lead independently. A strong example of integrating early warning triggers into operational governance, with community involvement before designing the plan, is the municipal Heat Action Plan in Dhangadhi, Nepal (see Box 2; Khan et al., 2025).

Box 2: From forecast to action - a municipal Heat Action Plan in Dhangadhi, Nepal

The Dhangadhi Heat Action Plan 2025 in Nepal provides a practical example of how an HEWS can be embedded within a municipal preparedness and response framework. Heat alert thresholds were developed using long-term temperature and humidity data combined with health data, applying the Heat Index to define trigger levels. These thresholds were directly linked to predefined preparedness and response measures, ensuring that forecasts translate into action.

Preparedness planning is both spatially and socially targeted. A heat hotspot analysis was conducted to identify high-risk wards, and a community heat perception study involving 984 household surveys and 25 focus group discussions was carried out to understand local experiences, coping strategies, and concerns related to extreme heat. These analyses informed the identification of vulnerable groups and priority areas for intervention. When the Department of Hydrology and Meteorology issues a heat alert, the municipal Heat Task Force coordinates cross-sectoral actions involving health services, water supply, electricity, education, disaster management committees, and the media.

Preparedness measures include identifying vulnerable populations, strengthening hospital capacity, developing ward-level response plans, and implementing communication campaigns. During heat events, actions include activating cooling centres, distributing water and cooling supplies, conducting outreach in high-risk areas, enforcing protections for outdoor workers, recording heat-related cases, and ensuring continued water and electricity supply to critical facilities. The plan also incorporates post-event assessments to evaluate effectiveness and inform improvements. In addition, it outlines longer-term measures to reduce underlying heat risk, including structural and planning interventions aimed at reducing exposure and strengthening adaptive capacity at the city level.

By linking locally defined thresholds, hotspot mapping, community perception data, and clearly assigned institutional responsibilities, the Dhangadhi HAP provides an excellent example of how a municipal HEWS can function as an operational governance mechanism.

Global coverage of HAPs/HHAPs remains uneven. A systematic review (1995–2020) identified formal HAP/HHAPs in only 47 countries worldwide, approximately 23 per cent of all countries, with most concentrated in Europe and parts of Southeast Asia, and none identified in Africa (Kotharkar and Ghosh, 2022; Figure 16). While most plans define a lead agency and alert mechanism, fewer include robust real-time surveillance, systematic evaluation, or integration with long-term urban planning and health system strengthening. Measures to address indoor heat exposure, social care capacity, or structural resilience are also often underdeveloped.

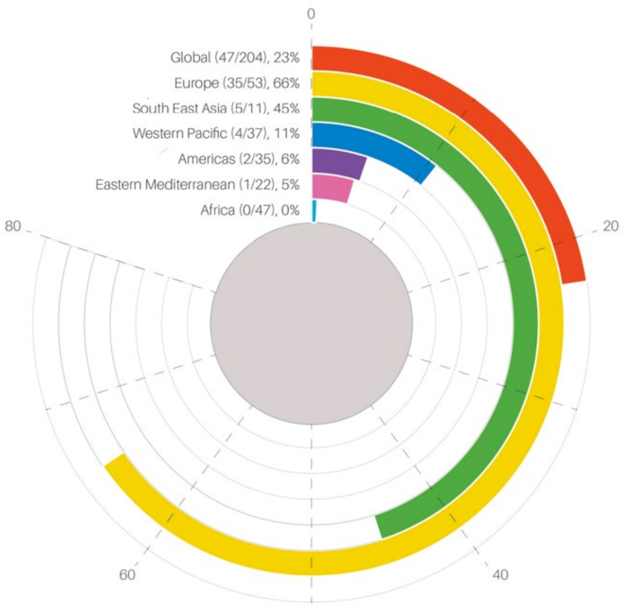

Figure 16 Distribution of existing HAPs/HHAPs. Source: Kotharkar and Ghosh (2022: 6)

A subsequent assessment of HHAPs across six countries found similar gaps: many HHAPs focus on short-term health-sector responses (e.g. public health messaging) and are reactive in origin, developed following severe heat events (GHHIN et al., 2025). Vulnerability assessments are often incomplete, funding mechanisms weak, and coordination across sectors such as infrastructure, labour, housing, and social protection limited. Without clear mandates, sustainable financing, and evaluation frameworks, plans may exist on paper but struggle during implementation, particularly in small municipalities with limited staff capacity.

Equity gaps are also evident. A 2025 review of 83 HHAPs across 24 countries found that, while children were frequently identified as at risk (83 per cent), fewer plans explicitly addressed pregnant individuals (52 per cent), newborns (39 per cent), or postpartum and breastfeeding populations (14 per cent) (Czerniewska et al., 2025). No plan comprehensively addressed maternal, newborn, and child health risks, and monitoring mechanisms were insufficient to assess impacts on these groups. These findings show that identifying vulnerable groups in policy documents does not automatically translate into targeted operational measures, reinforcing the need for more systematic integration of equity considerations within preparedness and response planning.

Furthermore, many HHWSs and plans have other limitations, including a strong focus on mortality as the primary indicator of impact. This focus is understandable, as mortality data are often the most consistently collected, standardized, and available health outcome across countries, making them a practical basis for threshold development and system activation. However, experts are increasingly calling for a shift beyond conventional mortality-focused approaches towards more adaptive, locally relevant, and targeted preparedness strategies (Matzarakis and Giannaros, 2025; Chandra and Lee, 2025). Recent commentary on the ‘next-generation’ of HHWSs and action plans emphasizes the importance of integrating thermo-physiological indices instead of temperature-only definitions, urban and indoor heat exposure, co-occurring environmental stressors, and socio-economic vulnerability into preparedness and response frameworks. These approaches recognize that heat impacts arise from cumulative exposure across daytime and night-time conditions, as well as interactions with other factors that can overwhelm health systems and critical infrastructure. Future HHAPs are therefore expected to place greater emphasis on morbidity, labour-related and socio-economic vulnerabilities, and continuity of essential services, alongside mortality reduction.

Anticipatory action and forecast-based financing for heat

In parallel to government-led HAP/HHAPs, anticipatory action frameworks and early action protocols (EAPs), largely developed within the humanitarian sector, are increasingly being applied to extreme heat. They link forecast triggers to predefined actions and financing, and are usually implemented within specific humanitarian programmes or pilot projects. As a result, they are often more limited in scope and duration, focusing on targeted high-risk areas. For example, (simplified) EAPs for heatwaves have been developed by the Red Cross Red Crescent movement in Greece, Kyrgyzstan, Hanoi in Vietnam, Dhaka in Bangladesh, and Tajikistan. While EAPs can demonstrate the value of anticipatory action, scaling and institutionalizing these approaches within government systems remains an important next step in many countries.

A practical example of anticipatory heat action is the Pakistan Heatwave Model developed under Start Ready by the Start Network (Start Network, 2022). The model links forecast-based Heat Index thresholds to pre-agreed contingency plans and automatically releases funding when trigger thresholds are forecast to be exceeded for consecutive days during the heat season. Pre-season planning defines mild, moderate, and severe response scenarios, with costed activities such as public awareness campaigns, mobile health units, heat-stroke camps, cooling centres, and targeted outreach to vulnerable groups, including elderly people, outdoor workers, and informal settlements. A defined governance structure, technical validation process, and rapid decision timelines ensure that forecasts translate into action before peak heat impacts occur. By combining forecast triggers, predefined financing, and locally developed contingency plans, the model illustrates how early warnings can be operationalized through anticipatory financing mechanisms rather than remaining purely informational.

Another example of a structured anticipatory action methodology that has been taken up by a national government is the Bangladesh National Early Action Protocol (NEAP) for heatwaves, which has been under development since 2025 (EIMS, 2025). The protocol combines hazard analysis (including percentile-based temperature thresholds and return period analysis), exposure mapping (population density, crop areas, livestock), and a weighted vulnerability index using socio-economic and physical indicators. Sector-specific triggers were developed through historical data analysis, field investigations, and forecast skill assessment. Early actions were identified and prioritized through field consultations and were ranked based on expected effectiveness, feasibility within lead time, and institutional capacity. The NEAP further defines two activation stages (readiness and activation triggers), pre-agreed financing pathways, and clearly assigned institutional responsibilities across ministries and local government. These approaches demonstrate how forecast triggers can be linked to automatic funding streams to accelerate response and reduce mortality and livelihood losses.

Multilevel governance and tiers of responsibility

Effective heat preparedness operates across multiple governance levels, each with distinct responsibilities. Clarifying these tiers is essential to avoid fragmentation and ensure that warnings translate into action. At the national level, governments typically define overall policy frameworks, set warning thresholds, coordinate meteorological and health services, and establish financing mechanisms. National authorities may develop overarching HAPs/HHAPs, define alert levels, and ensure alignment with disaster risk reduction and climate adaptation strategies. The broader institutional and governance conditions that enable these functions are discussed in more detail in the Effective governance and institutions section on page 43.

At the regional and municipal level, responsibilities often shift towards operational implementation of HAPs. Local authorities may open cooling centres, conduct targeted outreach, adjust public services, enforce labour protections, and coordinate local emergency response. Because both heat hazard and vulnerability patterns vary significantly across regions and within cities, localization of preparedness and response is critical. Geographic differences in climate, urban heat islands, housing conditions, access to cooling, and social vulnerability mean that the same national warning may require very different actions in different locations. Municipalities therefore play a central role in interpreting national alerts and adapting measures to local risk profiles, resources, and governance capacities.

At the community and institutional level, actors such as health clinics, schools, care homes, NGOs, faith-based organizations, and Red Cross/Red Crescent branches implement front-line protective measures. These actors are often best positioned to identify at-risk individuals. At the household and individual level, protective behaviour, hydration, modifying activity, and checking on neighbours remains essential. However, relying solely on individual responsibility is insufficient and inequitable. Higher tiers must enable action through infrastructure, services, and financial support.

Clearly mapping roles across these tiers, linking them to trigger thresholds, and ensuring accountability mechanisms are in place strengthens the operational effectiveness of HEWSs.

Sector-specific preparedness and planning for compounding impacts

Heat affects multiple systems simultaneously and produces cascading impacts across interconnected systems. Peak electricity demand for cooling can strain grids and increase the risk of outages, which in turn disrupt cooling centres, water supply systems, and digital communications. Transport infrastructure may degrade under prolonged heat stress. These compounding risks underscore the need for cross-sectoral coordination and contingency planning.

Different sectors may also have tailored response protocols once a heat warning is in place. Cross-sectoral coordination is particularly critical. In the health sector, preparedness may include activating heat-stroke triage protocols, increasing staffing in emergency departments, strengthening syndromic surveillance, and coordinating ambulance services. Energy providers may implement peak demand management strategies and prioritize electricity supply to hospitals and cooling centres. Schools and care institutions may adjust schedules or implement indoor cooling measures. Labour ministries may enforce work-rest cycles or temporary midday work bans for outdoor workers. Social protection systems can temporarily scale up cash or food assistance to vulnerable households.

Monitoring, learning, and accountability

HAPs and HHAPs must be periodically reviewed and tested, yet global assessments show that monitoring and evaluation are weak or absent in many plans (Kotharkar and Ghosh, 2022). After-action reviews, simulation exercises, and mortality and morbidity analyses can identify whether trigger-action protocols functioned as intended and whether vulnerable groups were effectively reached. International networks such as the GHHIN facilitate knowledge exchange and maintain repositories of HAPs/HHAPs, supporting peer learning across countries and regions.[6]

Pillar 4 gaps and challenges

Despite growing recognition of heat as a major risk, preparedness remains uneven globally. Many countries lack formal HAPs, sustainable financing mechanisms, or clear cross-sectoral mandates. Where plans exist, implementation gaps, limited evaluation, and insufficient integration of GESI considerations often reduce effectiveness. Plans remain focused on short-term health-sector responses, with weaker integration of social protection, labour policies, infrastructure resilience, and long-term urban planning. Strengthening this pillar requires institutional clarity, anticipatory and sustained financing, stronger sectoral coordination, and systematic inclusion of vulnerable

[6] For more information see the GHHIN website: https://heathealth.info/heat-action-plans-and-case-studies/

populations in operational planning. It also requires linking short-term emergency preparedness with longer-term risk reduction and adaptation, ensuring that warnings translate into both immediate protective action and structural resilience over time.

Enabling components for effective heat early warning systems

The four main pillars of an EWS are supported by four enabling components that ensure systems are coherent across multiple hazards, address gender and social inequalities in an inclusive way, involve local communities in their design and implementation, and are supported by effective governance and institutions.

Multi-hazard approach

Heat hazards interact with air pollution, humidity, drought, wildfires, storms, and floods, creating cascading and compounding risks. These interactions can take different forms (Budimir et al., 2025): triggering, when heat increases wildfire likelihood or contributes to electricity grid failure; amplification, when heat combines with high humidity or air pollution to intensify physiological stress and mortality risk (Red Cross Red Crescent Climate Centre, 2023); compound events, when heat coincides with hazards such as wildfire smoke or drought, requiring harmonized risk communication; and consecutive events, when heatwaves follow storms or floods and exacerbate already weakened infrastructure and reduced coping capacity (Singh et al., 2025). For example, after Hurricane Ida in 2021, prolonged power outages coincided with a heatwave in Louisiana, limiting access to air conditioning and contributing to heat-related mortality (Ouyang et al., 2025). Despite these well-documented interdependencies, many EWSs continue to treat hazards separately rather than as interconnected processes unfolding across time and space (Budimir et al., 2025).

Importantly, different hazards have distinct temporal dynamics, predictability, visibility, and behavioural responses, which shape the design and effectiveness of EWSs. For example, floods are often rapid onset and visually evident, while heat is gradual, largely invisible, and may require sustained communication and preparedness over days or weeks (see Box 3). These differences influence forecast lead times, communication strategies, and the types of early actions that are feasible. Recognizing similarities and differences across hazards can help avoid one-size-fits-all approaches and support more coherent, context-sensitive early warning and risk management.

A multi-hazard risk management approach therefore requires embedding heat within broader early warning architectures. This includes harmonized thresholds across sectors, coordinated dissemination protocols, shared data platforms, and aligned early action procedures. It also requires anticipating compound and cascading risks while accounting for dynamic exposure and vulnerability. Although global initiatives increasingly promote multi-hazard early warning systems, translating this ambition into operational integration remains challenging (Budimir et al., 2025). Strengthening multi-hazard coordination can reduce maladaptation, prevent conflicting guidance, and ensure responses are proportionate to cumulative risk rather than to hazards considered in isolation.

Box 3: Comparing flood and heat EWSs

Flood early warning systems (FEWSs) and HEWSs share the same overarching goal of reducing risks through enabling timely anticipatory action and preparedness (Painter et al., 2025). However, they differ substantially due to the distinct nature of the hazard, their institutional maturity, and the level of public risk literacy. These differences shape the design of each system.

	FEWSs	HEWSs
Hazard onset and lead time	Fast onset events and short lead times (e.g. five to eight hours). In some contexts, limited modelling capacity and monitoring infrastructure constrain timely warnings.	Slow-onset hazard with longer lead times (typically two to five days). Monitoring and forecasting exist in many countries, but heat is not always institutionalized within formal EWS structures.
GESI and vulnerability profiles	Flood vulnerability is often driven by physical exposure, housing conditions, and access to evacuation and shelter, with protection risks and mobility barriers affecting women, children, persons with disabilities, and marginalized groups.	Heat vulnerability is more closely linked to physiological sensitivity, health status, occupation, and social isolation, requiring stronger emphasis on targeted outreach, social care, occupational safety, and access to cooling.
Risk perception and public awareness	Flood literacy is often strengthened through community learning, and FEWSs are typically embedded within flood risk reduction strategies. Awareness and comprehension varies across vulnerable groups.	Heat risk is frequently normalized in countries historically affected by high temperatures, and heat is not consistently perceived as a hazard. Public awareness of health impacts is generally lower, with messages often not tailored to at-risk groups.
Institutional maturity	Many FEWSs operate continuously and have established governance arrangements. Some incorporate preparedness funds and IBF.	HEWSs are usually seasonal. Recognition of heat as a hazard may be inconsistent, resulting in gaps in the governance system. Humanitarian actors may step in where structures are lacking.

Thresholds and triggers	Multilevel rainfall or water level thresholds linked to specific triggers are typically relied on. Many systems are transitioning from hazard-based to impact-based approaches.	Thresholds differ across countries (e.g. maximum temperature, HI, WBGT). For heat EWSs, systems are transitioning to impact-based approaches.
Communication	Use of diverse communication channels. However, floods can disrupt power and telecommunications, highlighting the need for contingency planning.	Multichannel communication is common, but lower perceived risk and frequent warnings may reduce responsiveness to heat alerts.
Anticipatory action	Often formalized through predefined triggers and EAPs linked to funding.	Anticipatory action for heat exists in many countries (e.g. cooling centres, outreach to vulnerable groups), but implementation may be inconsistent and not always embedded in formal frameworks.

Gender and social inequalities addressed inclusively

Extreme heat does not affect everyone equally. Risk is shaped by layered vulnerability, and GESI considerations influence every component of an HEWS – not only who is at risk but who is reached, who can act, and who is ultimately protected (Romanello et al., 2024; Arrighi et al., 2025). Across the four pillars of an EWS, GESI considerations shape what risk information is produced (and for whom), how thresholds are defined, whether messages reach and resonate with those most at risk, and whether warnings activate targeted and feasible support measures.

Across Pillar 1 (disaster risk knowledge), equity depends on whether heat risk assessments capture differences in exposure, sensitivity, and coping capacity across gender, age, disability, occupation, socio-economic status, housing conditions, and urban–rural contexts. In many countries, such disaggregated data remain limited or outdated, constraining the ability to identify vulnerability pathways and design equitable interventions. Heat risk perception also varies strongly across population groups and intersecting identities, influencing whether warnings are received, trusted, and acted upon, yet evidence remains focused on higher-income countries. Making risk knowledge accessible is an inclusion issue: translating information into local languages, using visual/low-literacy formats, and co-developing risk tools (e.g. maps) with intended users helps ensure vulnerable groups are not excluded by technical language or institutional blind spots. Community-based and qualitative evidence is essential for equity where formal data systems are weak; it helps identify vulnerability pathways and lived constraints that may be invisible in national datasets.

Across Pillar 2 (observations, monitoring, analysis, and forecasting), observational blind spots can reproduce inequity: official station networks may under-represent urban hot spots, while indoor heat – highly relevant for caregivers, infants, older adults, and people spending long periods at home – is rarely monitored systematically. Many systems rely on population-level thresholds that reflect an ‘average’ level of risk, yet harmful impacts occur at lower thresholds for certain groups, such as older adults, people with chronic illness, pregnant women, children, outdoor and informal workers, and people living in poorly ventilated or overcrowded housing. Rather than lowering thresholds uniformly and risking warning fatigue, a more equitable approach is to pair broad public alerts with vulnerability-informed outreach and/or HHWSs for specific groups and/or health outcomes.

Across Pillar 3 (warning dissemination and communication), inclusive warning delivery requires multichannel strategies that overcome barriers in connectivity, literacy, language, disability access, and trust. In addition, they should leverage ‘first-mile’ pathways through trusted intermediaries such as community health workers, schools, local radio, faith-based organizations, and humanitarian volunteers. Message content must reflect lived realities: generic advice, such as ‘find somewhere cool’, can be inequitable when individuals lack access to cooling, time autonomy, or safe alternatives. Heat warnings should acknowledge constraints and clearly communicate available support. Equity-focused evaluation is needed and should assess not just whether warnings were issued, but whether different groups received, understood, trusted, and acted, and which channels worked for whom. Targeted or personalized approaches risk widening inequality if they rely solely on technologies such as sensors, apps, and digital access; they should complement, not replace, low-tech, community-based outreach.

Finally, across Pillar 4 (preparedness and response capabilities), GESI considerations remain unevenly integrated. Many low- and middle-income countries still lack formal HAPs/HHAPs, and where plans do exist, they often identify vulnerable groups without translating this into targeted support. For example, many plans mention children, but fewer address pregnancy, newborns, and postpartum or breastfeeding mothers. In addition, monitoring and tailored support mechanisms are weak, so gaps persist in practice. Warnings should trigger targeted support measures, such as outreach to socially isolated older adults, workplace protections for outdoor workers, and adaptations in maternal and child health services, linked to clearly assigned responsibilities across national-to-local tiers. Because implementation often rests with municipalities and community institutions where capacity may be limited, strengthening vertical coordination and resourcing for local actors is essential.

These challenges are compounded by broader structural inequalities. Some populations face barriers to receiving and acting on warnings due to language, literacy, digital exclusion, mobility constraints, or precarious employment conditions. Outdoor and informal workers may experience prolonged exposure while having limited flexibility to modify working hours or income. Women in many contexts bear disproportionate caregiving responsibilities, increasing indoor heat exposure, while low-income households are less likely to have access to cooling or heat-adapted housing. People with disabilities, older adults, and young children may face mobility and access barriers to cooling centres or public services. These intersecting social, economic, and physiological factors create layered vulnerabilities that HEWSs must explicitly account for. Geographic inequalities are also important. While much attention focuses on urban heat and the UHI effect, peri-urban and rural populations may face significant risks due to limited access to health services, early warning dissemination channels, social care systems, and infrastructure. Tailored approaches are therefore needed across both urban and rural contexts.

Box 4: Community perspectives of heat and weather warnings for pregnant and postpartum women in Kilifi, Kenya

Recent qualitative research in coastal Kenya highlights the importance of understanding gendered and life-course vulnerabilities to heat (Lusambili et al., 2024). Pregnant and postpartum women face specific exposure and health risks, yet often have limited access to timely and tailored heat and weather information. Barriers include low ownership of communication devices, language and literacy constraints, and gendered time burdens that reduce access to radio or community meetings. The study also found that trusted intermediaries, such as community health volunteers, mothers-in-law, and local leaders, play a critical role in reaching women and influencing behaviour, showing the importance of embedding heat early warnings within existing social and care networks.

Taken together, embedding GESI across all pillars helps ensure that HEWSs do not inadvertently reinforce existing inequalities but instead translate early warning into protective action for those most at risk and least able to adapt. This requires moving beyond awareness raising towards systemic, inclusive, and context-specific approaches that link warnings to social protection, public health, labour policy, and long-term resilience (Figure 17).

Disaster risk knowledge

- Develop a risk assessment that is intersectional using a gender equality and social inclusion lens and uses participatory approaches.
- Tailor information to accommodate diverse needs.
- Use trusted individuals and/or community leaders to build awareness.

Observations, monitoring, analysis, forecasting

- Use indigenous and/or local knowledge in monitoring systems.
- Improve accessibility of forecasting tools and warnings.
- Increase knowledge of heat alerts.
- Tailor heat alert levels to GESI-specific communication and early action protocols.
- Develop inclusive feedback mechanisms.

Warning dissemination and communication

- Use multiple outreach methods.
- Translate warnings into multiple languages.
- Use simple and clear messaging that are in accessible formats, including visuals and audio.
- Include low-tech and no-tech dissemination methods.

Preparedness and response capabilities

- Design cooling centre plans that are inclusive, accessible, and safe for all.
- Provide targeted support to vulnerable groups.
- Train emergency response personnel specifically on GESI considerations.

Figure 17 Example of GESI considerations for HEWSs. Source: Zurich Climate Resilience Alliance

Local community involvement

Communities are the first to experience and deal with the impacts of extreme heat. Their perceptions, coping strategies, social networks, and daily practices largely determine whether warnings translate into life-saving responses. Importantly, communities possess local knowledge about microclimates, vulnerable individuals, housing conditions, informal work patterns, and culturally appropriate coping mechanisms (Arrighi et al., 2025). In many contexts, residents already adapt to heat exposure through behavioural adjustments, social support systems, or informal early signals. Recognizing this local expertise shifts HEWSs from a one-directional dissemination model to a co-produced risk governance approach.

Traditional and Indigenous knowledge can play an important role in strengthening HEWSs, yet the evidence base on heat-specific traditional and Indigenous knowledge is limited. In many regions, communities have long observed environmental and seasonal indicators linked to extreme heat, such as changes in wind patterns, vegetation, water availability, animal behaviour, or locally defined seasonal calendars, which signal the onset and progression of hot periods. These knowledge systems can complement scientific forecasting by providing locally grounded insights into how heat is experienced, which periods are most critical for livelihoods, and which population groups are most exposed. This can support the co-development of locally relevant impact thresholds, improve vulnerability profiling, and help tailor warnings to the timing and decision contexts of specific sectors, such as agriculture, outdoor labour, or pastoralism. Traditional knowledge can also enhance communication and preparedness by informing culturally appropriate messaging, trusted dissemination channels, and locally feasible adaptation measures, such as adjusting daily routines, modifying housing and shading practices, or using locally available cooling strategies. Integrating these perspectives can improve trust, uptake, and behavioural response to warnings. Meaningful collaboration requires careful and respectful engagement, recognition of knowledge ownership, and approaches that avoid extractive or tokenistic use of local knowledge.

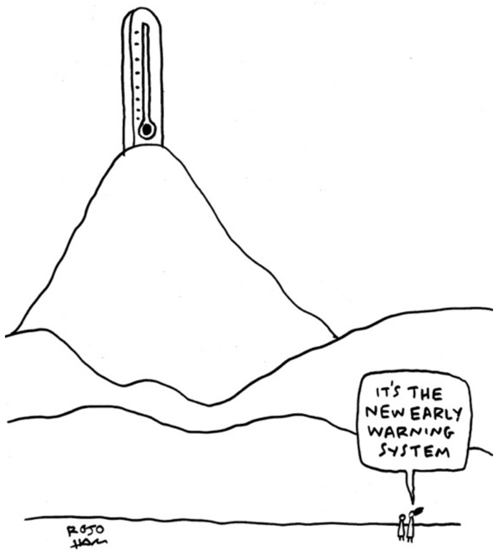

Figure 18 Cartoon on heat early warnings. Source: Syed et al. (2022)

Furthermore, despite widespread endorsement of the concept of people-centred EWSs, community participation in all pillars of HEWSs remains limited. Ambiguity around what meaningful participation entails, and limited local resources, can constrain sustained involvement.

Effective HEWSs require bridging institutional strength with community agency. Diverse local stakeholders that represent diverse vulnerable groups should be involved in defining locally relevant thresholds, identifying vulnerable populations and how heat impacts them, tailoring communication strategies, and operationalizing response actions such as activating cooling centres, neighbourhood outreach, or workplace adjustments. Community participation can strengthen public awareness campaigns, enhance cultural relevance, and improve the implementation of context-specific HAPs/HHAPs. Research shows that misalignment between institutional expectations and community needs can undermine trust and uptake. Sustained engagement across all four pillars therefore enhances collective ownership, trust, and adaptive capacity. Without meaningful local involvement, even technically sound warnings risk limited behavioural response and will therefore be less effective.

Effective governance and institutions

Extreme heat governance refers to the systems, institutions, policies, actors, and assets that shape how societies prepare for, respond to, and reduce heat-related risks, with HEWSs forming a core operational component within this broader framework. Unlike sudden-onset hazards, heat is often perceived as an 'invisible danger', resulting in a fragmented, reactive, and under-resourced governance response (Arrighi et al., 2025). Responsibilities are frequently dispersed across public health, meteorological services, disaster risk management, urban planning, labour, energy, and social protection sectors, with limited mechanisms for sustained cross-sectoral coordination (Arrighi et al., 2025; WMO, 2025). Therefore, heat remains under-recognized in policy, under-prioritized in adaptation planning, and under-resourced in local implementation, despite growing impacts.

Many governance attributes relevant for broader heat risk management are also critical for the effective design and operation of HEWSs. Recent frameworks highlight several core governance attributes necessary for effective overall heat risk management: leadership; laws and policies; coordination; knowledge systems; stakeholder involvement; and sustainable financing (Podesta et al., 2026). Clear leadership and defined mandates are critical to avoid ambiguity over roles and accountability. Without a designated coordinating body or 'problem owner', heat action risks remaining ad hoc and crisis driven. HAPs, for example, are most effective when they bring together multiple institutions under a designated coordinating authority to ensure unified and sustained implementation (Arrighi et al., 2025). Embedding HEWSs within formal legal and policy frameworks, such as disaster risk legislation, occupational safety standards, urban planning codes, and national or subnational HAPs/HHAPs, strengthens effectiveness.

Governance challenges are particularly evident across scales. While national meteorological services typically lead monitoring and forecasting, preparedness and response actions are often implemented at regional or local levels, where resources, mandates, and capacities may be limited. Weak vertical coordination can lead to gaps between national-level warnings and locally appropriate action, especially in decentralized systems. Strengthening governance arrangements that link national forecasting with local decision-making, community engagement, and context-specific action planning is therefore essential.

Effective governance also requires operationalizing action across timescales. The recent UNDRR *Extreme Heat Risk Governance: Framework and Toolkit* emphasizes a cyclical process: generating demand for action; planning inclusively; implementing coordinated measures; and institutionalizing learning and improvement (WMO, 2025). This highlights that HEWSs should not function as standalone technical systems, but as part of an iterative governance cycle linking early warning to preparedness, response, evaluation, and long-term adaptation.

Sustained financing and institutional continuity remain persistent gaps (Arrighi et al., 2025; WMO, 2025). Many heat adaptation initiatives are implemented as time-bound, project-based efforts, often dependent on external or donor funding and lacking strong national policy anchoring. While such projects may generate valuable data, partnerships, and practical experience, their long-term impact is frequently constrained. A recent report illustrates how successful heat action journeys, such as in Nepalgunj, Nepal, required sustained collaboration and eventual municipal budget allocation to move beyond pilot phases and ensure durability (Arrighi et al., 2025).

Synthesis and conclusions

The development of HEWSs across the four pillars highlights substantial progress over recent decades, but also persistent and emerging gaps.

Heat risk knowledge has expanded, particularly in hazard monitoring and health impacts. In most regions, hazard information is relatively strong, yet impact evidence remains heavily focused on mortality, with less attention to infrastructure, labour, energy, agriculture, and livelihoods. Temperature is among the most predictable weather variables - predictable one week in advance - creating important opportunities for anticipatory action. However, the current diversity of heat metrics, definitions, and thresholds across countries limits comparability, operational coherence, and effective risk monitoring and communication.

Heat also presents distinct communication challenges. Its largely invisible and gradual nature contributes to low risk perception, requiring sustained investment in heat literacy, seasonal awareness, and behaviourally informed communication. Extreme heat can also strain power systems, increasing the risk of outages and undermining digital warning channels, which highlights the importance of redundant and community-based communication pathways. Even where heat-warning systems exist, they are not always linked to predefined actions. Although more countries and cities are developing HAPs/HHAPs, global coverage remains uneven and implementation gaps persist. Many existing plans also insufficiently address diverse at-risk populations or systematically integrate gender and social inequalities. To address some of these gaps, humanitarian anticipatory action and EAPs have demonstrated the value of linking forecasts to predefined actions and financing; however, these are often geographically and temporally limited.

Greater attention needs to be paid to the compounding nature of heat risk, including interactions with air pollution, drought, and floods. Across all pillars, meaningful community involvement remains limited and should extend to the co-design of warning systems, communication strategies, and preparedness measures. Finally, governance remains a critical foundation. Clear mandates, cross-sectoral coordination, sustained financing, and institutional learning are essential to strengthen heat early warnings. Monitoring and evaluation of HAPs are weak in many contexts, despite the need to adapt systems to changing climate, demographic, and vulnerability patterns. Expanding coverage to underserved regions, strengthening implementation, and fostering continuous learning across countries will be key to ensuring that HEWSs translate into effective and equitable protection.

Emerging innovations

The previous section highlighted substantial progress in the global expansion of HEWSs but also revealed important gaps: limited impact orientation; uneven integration with health data; challenges in reaching vulnerable populations; and fragmentation in data, governance, and evaluation.

Against this backdrop, several emerging innovations are gaining traction. However, many of these approaches remain at an early stage of development, are primarily concentrated in high-resource settings, and are often implemented as pilot or experimental applications. Nonetheless, they indicate a shift beyond generic temperature-based alerts towards more impact-oriented, targeted, and technologically enabled systems. The following subsections highlight key developments that may influence how heat is forecasted, communicated, and acted upon.

Impact-based forecasting for heat

IBF is an approach that goes beyond predicting what the weather will *be*, to focus on what the weather will *do* (WMO, 2021). Instead of forecasting variables such as temperature, wind speed, or rainfall, it combines meteorological information with exposure, vulnerability, and impact data to estimate potential outcomes. These may include health effects, infrastructure stress or damage, and increased demand for emergency and public services. By anticipating impacts in advance, IBF can support more targeted preparedness, resource allocation, and early action.

Although IBF can be applied across sectors, heat-related health forecasts have been most widely studied to date. This reflects both the strong evidence linking heat and mortality and the central role of public health in many HEWSs. Health forecasts offer a significant opportunity to strengthen heat and health EWSs and their corresponding action plans, and international experts have argued such forecasts should be an intrinsic component of HHWSs (Royé et al., 2026).

Research has demonstrated that the predictability of temperature forecasts can be translated into skilful forecasts of heat-related mortality. For example, statistical temperature–mortality models combined with ensemble weather forecasts have shown useful predictive skill across Europe, with lead times of around one week, depending on season and location (Zamorano et al., 2024; Holmberg et al., 2025). Similar approaches have been explored at finer spatial scales, including near-neighbourhood applications in the UK (Gasparrini and Mistry, 2024). Methods to forecast heat-related health outcomes range from established epidemiological models to more advanced machine-learning approaches (Boudreault et al., 2023). Despite this growing evidence base, operational implementation remains limited. Although regional mortality forecasts now exist in some contexts, including Europe (Figure 19; Ballester et al., 2024), they are not yet systematically integrated into warning thresholds or linked to the activation of heat-health action plans.

Box 5: Operational heat-related mortality forecasts for Europe

One example of an operational heat-health forecast is the open-access platform Forecaster. Health, which provides temperature- and air-pollution-related mortality warnings across Europe, including disaggregation by age and sex (Ballester et al., 2024). Forecast skill for health impacts broadly follows that of temperature, with useful predictability typically extending up to about one week.

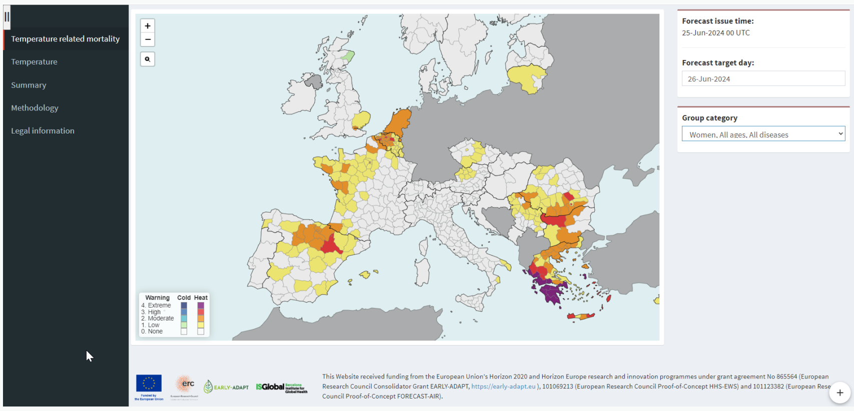

Figure 19 Operational temperature-related mortality forecast across Europe. Source: Ballester et al. (2024)

However, important barriers remain for IBF in general and for heat-specific IBF (Potter et al., 2021). Key challenges towards operational IBF include limited availability and accessibility of impact, exposure, and vulnerability data; difficulties in verifying forecasts and measuring avoided losses; governance and responsibility constraints; and the costs and institutional capacity required to operationalize these systems. For heat-health forecasting, even in countries with strong health surveillance and high-quality historical health data, producing and using such forecasts operationally is not easy. A recent study showed large methodological diversity across countries for estimating heat-related mortality, with differing definitions, data sources, and modelling approaches, which limit the development of such forecasts (Royé et al., 2026). In low- and middle-income countries, the barriers towards developing IBF are even more acute; fragmented (health) surveillance systems, limited disaggregated data, and competing priorities and limited resources constrain development and implementation of IBF. As a result, despite strong potential, the development, validation, and operational use of robust heat impact forecasts remains limited and is likely to remain uneven globally without sustained investment in data systems, institutional coordination, and capacity development.

Towards targeted, personalized HEWSs

Most existing HEWSs operate at the national or population level, using certain meteorological thresholds to trigger alerts and public messaging; these systems serve as the critical first layer of warning, activating institutional preparedness, yet may fall short in addressing the diversity of exposures and vulnerabilities within a population (O'Connor et al., 2025). National HEWSs may not adequately account for intra-urban temperature differences, indoor exposure, or the specific needs of high-risk groups such as older adults, pregnant women, children, people with disabilities, people with pre-existing medical conditions, or outdoor workers. Warnings are typically issued for large regions, but local heat conditions may vary significantly due to factors like UHIs, housing quality, or access to cooling. Additionally, population-level messages are usually one-size-fits-all and may not effectively reach or engage those who are most at risk. These gaps limit the ability of national HEWSs to drive timely and targeted action, especially in densely populated or socio-economically diverse settings, highlighting the need for complementary, more tailored services.

In response, there is growing interest in more personalized heat early warning approaches that tailor alerts and advice to a person's specific health profile, daily activities, and environmental exposure. There are several examples that use wearables, mobile technology, and predictive modelling to issue customized alerts, nudges, and behavioural guidance, such as ClimApp in Europe (Kingma et al., 2021; Eggeling et al., 2022); a prototype personalized heat EWS for Delhi, India (Kacker et al., 2025); California's CalHeatScore; and the HeatWatch app piloted in Sydney (Jay et al., 2025) (see Box 6). In the Netherlands, developments are underway to provide more targeted heat risk advice by introducing a 0–10 WBGT-based scale that can be coupled with personal or sectoral heat risk factors. These systems can increase perceived risk, motivate protective action, and close the gap between vulnerability and action at the individual level.

Box 6: HeatWatch pilot in Sydney, Australia

The HeatWatch pilot, led by the University of Sydney's Heat & Health Research Centre and launched in 2023, is an example of how personalized digital tools can strengthen HEWSs (Figure 20). Developed in partnership with the NSW Reconstruction Authority and community organizations, HeatWatch provides individualized heat-health risk assessments through a mobile app. Its design and features are shaped by direct consultations with community members via focus groups, including adults older than 70, families with young children, and pregnant women, as well as investing in testing and co-design with Indigenous communities across Australia.

Users enter basic personal information, such as age, health conditions, access to cooling, and planned activity, while the app ingests local meteorological forecasts (temperature, humidity, solar radiation, wind) to calculate a personalized heat-stress risk score.

Unlike conventional heat alerts that apply uniformly to whole regions, HeatWatch tailors advice to the user's actual level of physiological risk. It offers practical, context-specific recommendations (e.g. when to avoid strenuous activity, cooling strategies for people without air conditioning, and when fans may or may not be effective). In doing so, the pilot illustrates an emerging shift from generic warnings to risk-informed, behaviour-oriented guidance.

The pilot also demonstrates how personalized tools can link to wider preparedness and response mechanisms. In Sydney's Surry Hills, a mobile cooling hub trial used HeatWatch risk thresholds to decide when to activate services for people experiencing homelessness, showing how individual risk information can support community-level action.

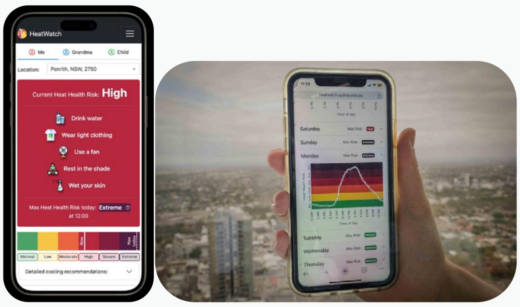

Figure 20 HeatWatch app. Source: https://heatwatch.sydney.edu.au/

While these personalized systems offer promising potential, a recent commentary also raises important concerns around equity, access, and governance (O'Connor et al., 2025; Figure 21). For example, not everyone has access to smartphones, wearables, or stable connectivity, particularly in low-income or older populations, and relying solely on app-based warnings risks excluding those most in need. More fundamentally, while individualized systems can supplement heat risk management, large-scale responses such as activating public cooling centres, health system alerts, or labour protections require trusted and authoritative national or local entities to issue warnings. These critical public safety functions cannot be outsourced to apps; they require centralized, accountable institutions to coordinate protective actions at scale. Still, personalized tools can complement population-level alerts with more context-specific guidance.

Population EWS		Individual EWS
National, regional or community level	Scale	Individual or household level
General public, high-risk populations broadly defined	Target audience	Specific individuals with unique risk profiles
Meteorological criteria (for example, maximum temperature, historical averages)	Alert triggers	Personal thresholds (for example, core temperature, heart rate, home temperature)
Broadcast media, SMS, newspapers, public-health messaging	Delivery mode	Apps, wearables, direct device prompts
Weather forecasting, public messaging infrastructure	System needs	Sensors, mobile connectivity, cloud analytics, user interface
• Wide reach • Low cost per person • Shown to reduce mortality	Strengths	• Supports autonomy • Early detection of individual risk • Tailored advice
• One-size-fits-all advice • Overlooks indoor risks • Depends on individual perception and action	Limitations	• Requires tech access and digital literacy • Cost and privacy concerns • Limited validation in diverse groups
Heatwaves in urban areas, especially where rapid, scalable messaging needed	Best use case	High-risk individuals (for example, older persons, those who are chronically ill) living in variable conditions
May underserve those with unique or hidden vulnerabilities	Equity concerns	May exclude those without access to devices or Internet

Figure 21 Comparison of population and individual HEWSs. Source: O'Connor et al. (2025)

Artificial intelligence and HEWSs

AI offers potential opportunities to improve the effectiveness and precision of HEWSs across all four EWS pillars, yet research on AI for heatwaves remains very limited compared to hazards like floods and wildfires. A recent review paper found that only 2.3 per cent of AI-EWS research papers focus on heatwaves or heat stress, far lower than the 50.6 per cent focused on floods, even though extreme heat is one of the fastest-growing and deadliest climate risks (Otero et al., 2026).

AI may strengthen Pillar 1 by integrating satellite imagery, land use, and demographic, health, and socio-economic data to develop high-resolution and dynamic heat exposure and vulnerability maps, detect hotspots, and identify at-risk populations. For Pillar 2, emerging AI-driven forecasting models can learn patterns from large historical datasets and can generate forecasts rapidly and with lower computational demand than traditional physics-based models; however, they still struggle to reliably capture record-breaking extremes, which are the events most critical for early warning (Zhang et al., 2025). AI can support Pillar 3 by translating warnings into multiple languages, tailoring messages and images to specific audiences, optimizing dissemination channels, and providing real-time guidance through chatbots or automated call systems. For Pillar 4, AI may help anticipate where service systems will be stressed – such as hospitals, energy grids, transport, and cooling centres – supporting proactive resource allocation and anticipatory action.

At the same time, important limitations and risks must be considered (Youds and REAP Early Warning Systems Working Group, 2025). Some AI models operate as 'black boxes', making it difficult for decision makers and communities to understand, trust, and act on forecasts. This lack of transparency and explainability can be particularly problematic in high-stakes decision contexts such as public health and disaster response. There are also concerns about bias, fairness, and accountability, as models trained on incomplete or unrepresentative datasets may reinforce existing inequalities or overlook vulnerable populations. These challenges are especially relevant in low- and middle-income and fragile contexts. Limited availability of local, high-quality data can constrain model performance, while digital divides, weak infrastructure, and low connectivity may restrict access to AI-enabled warning services. Ethical and governance challenges around data ownership, privacy, and regulatory oversight are also more difficult to address in such settings. Without strong institutional frameworks, there is a risk that AI could shift power away from local authorities or communities, or lead to over-reliance on external actors and proprietary technologies. Ensuring that national and local institutions remain the authoritative source of warnings is therefore essential.

Finally, effective AI use requires strong human–machine collaboration. Human expertise remains critical for contextual interpretation, ethical oversight, and translating forecasts into actionable guidance. Piloting AI in specific contexts, co-designing tools with local stakeholders, and embedding safeguards for equity and transparency will be essential to ensure that AI strengthens rather than undermines people-centred HEWSs. Overall, while there is strong potential to improve aspects of HEWSs, it remains at an early stage. Advancing responsible use will require targeted investment, rigorous evaluation (especially for extremes), safeguards around bias and equity, and closer collaboration between meteorological, health, humanitarian, and social protection actors.

Figure 22 A 55-year-old cleaner wipes sweat during unbearable heat in the New Territories district, Hong Kong, on 9 July 2024 (from the GHHIN-EJN Extreme Heat Photo Contest 2025). Photo: Kyle Lam

Recommendations for strengthening HEWSs

As HEWSs continue to expand and evolve globally, evidence from existing reports and this analysis highlights key areas for improvement (Kotharkar and Ghosh, 2022; GHHIN, 2023a; Chandra and Lee, 2025; Matzarakis and Giannaros, 2025; WMO, 2025). The recommendations below address identified gaps and aim to support countries in strengthening both the technical design and implementation of people-centred systems.

Recommendation 1: Embed meaningful and inclusive community participation

Most HEWSs remain largely top-down, with limited structural engagement of communities. Community knowledge is crucial to help ensure warnings are relevant, trusted, and actionable. Participation can be integrated through methods ranging from participatory vulnerability mapping, co-development or testing of warning messages, engagement in preparedness planning, and feedback after warnings. Community involvement can also be leveraged to strengthen local heat monitoring, for example, through citizen weather stations that can support more locally relevant heat warnings. Diverse participation and representation are essential. Responsibility for meaningful engagement is shared across meteorological services, public health authorities, municipalities, and humanitarian and civil society actors. Institutionalizing these mechanisms can help move beyond ad hoc consultation towards continuous and adaptive engagement.

Recommendation 2: Strengthen heat risk knowledge and integration into warning systems

Although heat risk knowledge is rapidly growing globally, significant local gaps remain. While heat-health research is relatively advanced, impact evidence across other sectors, such as labour productivity, energy systems, agriculture, water, infrastructure, and ecosystems, remains fragmented and underdeveloped (Brogno et al., 2025). In many low- and middle-income settings, basic epidemiological evidence on heat impacts is still scarce. Strengthening impact knowledge requires collaboration and data sharing between meteorological services and sectoral actors, such as transport, labour, health, energy, and agriculture, to better understand the consequences of extreme heat. Qualitative assessments and local knowledge from practitioners, community-based organizations, and humanitarian actors are also essential. Risk assessments should be linked to GESI analysis to better identify at-risk groups and inform targeted warnings and protective actions. Stronger heat risk knowledge across global, national, and local scales is essential to identify who is most at risk and ensure warnings translate into timely and effective action.

Recommendation 3: Improve understanding and use heat metrics and thresholds

Countries currently use a wide range of approaches to define and measure heat, with a lack of consistent and context-appropriate methods, including for heatwaves. However, the choice of heat metric matters, as it affects what type of heat is identified, how far in advance warnings can be issued, and which impacts they best relate to. Experts increasingly emphasize that heatwave definitions should account for cumulative heat across both day and night, which is not captured by single indicators such as maximum temperature alone (Brogno et al., 2025; Nairn and Mason, 2025; Pereira Marghidan et al., 2025). In addition, approaches that link heat to health outcomes also vary widely, even in regions such as Europe with long-standing systems and strong data, reflecting the lack of standardized methods (Royé et al., 2026). Overall, there is a clear need to strengthen and better align methods for defining and measuring heat, including how health evidence is used. In addition to public-facing warnings, heat services should be expanded using complementary metrics tailored to sector-specific risks and decision needs. Lastly, systems should be regularly evaluated to ensure that metrics and thresholds reflect real impacts and support decision-making. Continuous monitoring, post-event review, and the use of new evidence can help refine thresholds over time, while combining complementary metrics and strengthening local validation can further improve relevance and consistency.

Recommendation 4: Ensure warnings are locally relevant

Heat-warning thresholds should be adapted to local climate conditions to better reflect variations in hazard and, where appropriate, population-level vulnerability. Even with advances in forecasting, weather models cannot fully capture neighbourhood-scale differences such as urban heat, indoor exposure, or microclimates. Local authorities and sectoral actors should therefore combine forecast information with exposure and vulnerability data to identify priority populations and locations, rather than relying on hazard information alone. Tools such as heat hotspot mapping, vulnerability assessments, urban heat and indoor risk analyses, and community knowledge can support more targeted preparedness and early action.

Recommendation 5: Ensure that warnings translate into action

Issuing a warning does not automatically result in protective behaviour or an effective institutional response. At the individual level, low risk perception, normalization of heat, economic constraints, or lack of access to cooling can limit behavioural responses. Frequent warnings without visible impacts may also contribute to warning fatigue and undermine their effectiveness. At the institutional level, heat warnings may fail to trigger concrete measures if there are no plans in place, or plans are unclear, under-resourced, or insufficiently coordinated. Plans require sustained investment, leadership, and cross-sectoral coordination beyond individual responsibility. Therefore, strengthening the link between warning and action through clearer action protocols, anticipatory financing mechanisms, and regular simulation exercises is recommended. Communication strategies should move beyond hazard information to emphasize impacts and actionable guidance, while sustained public awareness campaigns across sectors can help reinforce understanding of heat risks. Monitoring behavioural uptake and institutional activation following warnings can provide critical feedback to improve effectiveness over time.

Recommendation 6: Strengthen understanding and management of seasonal and chronic heat risk

Current heat frameworks and warnings are primarily designed for acute heatwaves and are ill-equipped for sustained heat regimes. In many regions, heat does not occur as a short-lived extreme but as persistent, seasonal exposure lasting months or longer at a time, resulting in cumulative physiological stress and chronic impacts on health and livelihoods. Traditional heatwave definitions are insufficient in such contexts, and evidence shows that chronic heat is expanding geographically, particularly in densely populated subtropical regions transitioning from acute to sustained heat regimes (Cruz et al., 2025; Fanning et al., 2025). In such regions, warning systems should move beyond purely event-triggered models towards seasonal and structural risk management approaches. Chronic heat exposure may affect population groups differently, with cumulative and unequal impacts on health, productivity, and livelihoods. This can include issuing seasonal heat outlooks, maintaining sustained outreach and protective services throughout the heat season or permanently, and embedding heat risk management within social protection, labour safety, housing, and energy governance frameworks.

Recommendation 7: Integrate heat into multi-hazard and systemic risk frameworks

Heat hazards interact with other hazards such as drought, wildfire, air pollution, and energy system stress. Developing HEWSs in isolation limits the ability to anticipate cascading and compound impacts. Heat warnings should therefore be embedded within multi-hazard early warning and disaster risk management frameworks, with explicit attention to hazard interactions and cross-sectoral interdependencies. Scenario planning for compound events and stress testing of infrastructure and service systems can strengthen preparedness.

Recommendation 8: Move beyond health-only systems towards cross-sectoral protection

HEWSs often focus primarily on health outcomes, which is logical considering the serious health consequences from heat. However, extreme heat affects energy systems, water supply, labour productivity, agriculture, transport, education, and emergency services. Limiting warnings to health framing can overlook risks to critical infrastructure and livelihoods. Strengthening cross-sectoral engagement is essential to ensure that warnings trigger protective actions across interconnected systems. Sector-specific thresholds, lead times, and EAPs should be co-developed with relevant ministries, utilities, and service providers. Layered warning approaches that combine public alerts with tailored sectoral guidance can better support decision-making while maintaining clarity for the general public. Coordinated cross-sectoral planning also helps reduce cascading impacts, strengthen the resilience of critical systems, and increase political and institutional ownership of heat risk management.

Recommendation 9: Strengthen governance, clarify roles, and secure sustainable financing

Across countries, fragmented institutional mandates, unclear trigger responsibilities, and weak coordination mechanisms remain a challenge that limits the effectiveness of heat warnings and heat governance as a whole (WMO, 2025). Leadership of heat governance should be anchored within national or regional government frameworks, with clearly defined roles across meteorological, health, disaster management, and local authorities, ensuring coordinated and accountable implementation across sectors. Standard operating procedures should link warnings directly to sectoral action plans at all levels. Dedicated and sustainable financing mechanisms, including anticipatory funding triggers, are essential to ensure that systems can be maintained, updated, and activated reliably. Embedding HEWSs within long-term governance and resilience planning strengthens institutional ownership and continuity.

Recommendation 10: Institutionalize monitoring, evaluation, and learning

Many HEWSs have been established following major heat events but are not systematically evaluated thereafter. Climate change, demographic shifts, public awareness and risk perception, and urbanization alter risk patterns over time, making continuous learning essential. Regular process and outcome evaluations should assess factors such as metric appropriateness, forecast skill, lead time, communication reach, equity of access, risk perception, behavioural uptake, population-level vulnerability, and measurable impact reductions. Lessons learned should inform updates to thresholds, metrics and indices, governance arrangements, communication strategies, and preparedness measures. Inclusive and accessible feedback mechanisms are also critical. Vulnerable groups should be actively engaged in sharing their experiences of warnings, including whether they were received, understood, trusted, and actionable, as well as the barriers to protective behaviour. This can help identify gaps in communication, accessibility, and response capacity. Embedding monitoring and evaluation within institutional mandates ensures that systems remain adaptive, accountable, equitable, and responsive to evolving risk (Hess and Ebi, 2016).

Conclusion

Extreme heat is a present and accelerating global risk, impacting people and sectors worldwide. HEWSs are critical tools to help governments and communities prepare and reduce impacts. Although these systems are expanding worldwide, around half of countries still lack formal HEWSs, and among those that do exist, there is wide variation in how systems are designed, governed, and implemented.

Through analysis of the four EWS pillars and enabling components, this report outlines the current landscape of HEWSs. Heat risk knowledge remains limited in many regions and is concentrated on hazard- and health-related evidence, with far less understanding of heat-related impacts across other sectors. Even when evidence exists, it is not always integrated into warning system thresholds or action protocols. Definitions of heat remain highly diverse. Greater consistency and transparency in the use of heat metrics, grounded in evaluation and local validation, are needed to support global coordination, cross-border comparability, and more effective HEWSs. This requires clearer guidance on metric selection across sectors, regions, and populations, while recognizing that multiple metrics can serve complementary purposes.

Although awareness of heat risks has grown worldwide, communicating heat remains a persistent challenge. Compared to many other hazards, heat is often predictable several days in advance, offering valuable lead time. However, communication is frequently still too generic and insufficiently tailored to specific audiences, limiting its impact on timely and protective action. Heat is also often portrayed in media and public discourse as positive or recreational, which can undermine risk perception and make it difficult to convey the seriousness of impacts. Effective systems must ensure that warnings reach and are understood by all, particularly those most at risk, and are directly linked to predefined institutional responses and targeted support measures.

Addressing current gaps requires deliberate institutional design, sustained financing, participatory approaches, and continuous learning. Climate change is increasing the frequency, intensity and geographical spread of heat, placing growing pressure on existing systems and urgently driving the need for coverage in regions where HEWSs remain absent. In many contexts, simple and feasible systems can be established, which can be strengthened over time as knowledge, capacity, and governance improve.

Strengthening HEWSs is one of the most immediate and scalable ways to reduce preventable heat-related impacts. Doing so requires balanced investment across all pillars and enabling components, anchored in people-centred design and long-term institutional commitment. As global temperatures continue to rise, well-designed and inclusive HEWSs offer a powerful opportunity to protect lives, livelihoods, and resilience in a warming world.

Appendix A

For each pillar, guiding questions were developed to support the analysis in this report and to inform the design and evaluation of HEWSs.

Pillar 1: key questions to assess and strengthen **heat risk knowledge**

1. Are historical and recent heat extremes well documented, and are future trends and projections (e.g. frequency, intensity, duration) understood?
2. Who is most exposed and vulnerable to extreme heat, and how are these patterns changing over time?
3. What are the observed and potential heat-related impacts across sectors (e.g. health, agriculture, energy, labour, ecosystems)?
4. How do different groups perceive extreme heat and its risks, and how does this influence protective behaviour and preparedness?
5. How is heat risk assessed, monitored, and updated? What data, mapping tools, and evidence are used?
6. To what extent are scientific data, local knowledge, and lived experiences integrated into practice and operations?
7. Are gender, age, disability, and other social factors reflected in risk assessments and data collection? Whose experiences or vulnerabilities are missing from existing analyses?

Pillar 2: key questions to assess and strengthen **observations, monitoring, analysis, and forecasting of extreme heat**

1. Are local weather stations in place?
2. What indicators are used to define and monitor extreme heat?
3. Are the right parameters being monitored?
4. How accurate and timely are forecasts?
5. Are forecasts linked to impacts?
6. Are forecasts available at the local level?
7. What role could and should local knowledge and inclusion of communities play in hazard monitoring?
8. How are different vulnerabilities included in heat-warning thresholds?

Pillar 3: key questions to assess and strengthen **heat-warning dissemination and communication**

1. Are the roles and mandates for issuing and disseminating heat warnings clearly defined and understood?
2. Do warning messages reach all groups, including those in remote areas or with limited connectivity?
3. Are multiple communication channels used to ensure timely and reliable dissemination?
4. Are heat warnings impact based and do they provide clear, actionable guidance?
5. Do local actors, volunteers, or community networks support first-mile communication?
6. Is feedback collected on whether warnings were received, understood, and acted upon?
7. Are warning messages regularly reviewed and improved?

Pillar 4: key questions to assess and strengthen **heat preparedness and response capabilities**

1. Do national and local plans include clear actions to be triggered when a heat warning is issued?
2. Are cooling centres and essential services planned and accessible based on heat risk assessments?
3. Are health, emergency, and social services prepared and equipped to respond during heat events?
4. Are preparedness plans participatory and inclusive of at-risk groups?
5. Are cascading impacts of extreme heat integrated into preparedness planning?
6. Are local responders supported with clear protocols and resources?

7. Are drills or simulations conducted regularly to test and improve heat preparedness?

References

Arrighi, J. et al. (2025) *Heat through the eyes of the most vulnerable: perceptions and pathways to action*, Red Cross Red Crescent Climate Centre, The Hague.

Ballester, M.Q.Z.J., Beas-Moix, M., Beltrán-Barrón, N., Méndez Turrubiates, R. and Peyrusse, F. (2024) 'Forecaster.health'. https://forecaster.health/.

Bauer, P., Thorpe, A. and Brunet, G. (2015) 'The quiet revolution of numerical weather prediction', *Nature* 525(7567): 47–55. doi: 10.1038/nature14956.

Boudreault, J., Campagna, C., and Chebana, F. (2023) 'Machine and deep learning for modelling heat-health relationships', *Science of the total environment* 892. doi: 10.1016/j.scitotenv.2023.164660.

Brogno, L., Barbano, F., Leo, L.S. and Di Sabatino, S., 2025. 'Review on heatwaves: a risk perspective', *Environmental Research Letters,* 20(6). pp. 0–14. DOI: 10.1088/1748-9326/add178

Budimir, M. et al. (2025) 'Opportunities and challenges for people-centered multi-hazard early warning systems: perspectives from the Global South', *iScience* 28(5): 1–15. doi: 10.1016/j.isci.2025.112353.

Burgstall, A., Casanueva, A., Kotlarski, S. and Schwierz, C. (2019) 'Heat warnings in Switzerland: reassessing the choice of the current heat stress index', *International Journal of environmental research and public health* 16(15). doi: 10.3390/ijerph16152684.

Campbell, S., Remenyi, T.A., White, C.J. and Johnston, F.H. (2018) 'Heatwave and health impact research: A global review', *Health & place* 53: 210–18. doi: 10.1016/j.healthplace.2018.08.017.

Casanueva, A. et al. (2019) 'Overview of existing heat-health warning systems in Europe', *International journal of environmental research and public health* 16(15). doi: 10.3390/ijerph16152657.

Cecinati, F., Matthews, T., Natarajan, S., McCullen, N., and Coley, D. (2019) 'Mining social media to identify heat waves', *International journal of environmental research and public health* 16(5). doi: 10.3390/ijerph16050762.

Chae, Y. and Park, J. (2021) 'Analysis on effectiveness of impact based heatwave warning considering severity and likelihood of health impacts in Seoul, Korea', *International journal of environmental research and public health* 18(5). doi: 10.3390/ijerph18052380.

Chandra, S.V.S.N. and Lee, J.K.W. (2025) 'A systematic review of heat health warning systems: enhancing the framework towards effective health outcomes', *Current environmental health reports* 12(1): 1–14. doi: 10.1007/s40572-025-00496-5.

Copernicus Climate Change Service (C3S) (2026) 'Global climate highlights 2025'. doi: https://doi.org/10.24381/b3nm-p354.

Correia, E., Henriques, C.D., and Correia, E. (2025) 'Indoor thermal comfort in informal settlements : a case study of Mafalala, Maputo', *African geographical review* 44(6): 558–80. doi: 10.1080/19376812.2025.2520775.

Cruz, M. et al. (2025) 'Where heat does not come in waves: a framework for understanding and managing chronic heat', *Environmental research: climate* 4(2). doi: 10.1088/2752-5295/adc827.

Cvijanovic, I., Mistry, M.N., Begg, J.D., Gasparrini, A. and Rodó, X. (2023) 'Importance of humidity for characterization and communication of dangerous heatwave conditions', *npj Climate and atmospheric science*, 6(1): 15–17. doi: 10.1038/s41612-023-00346-x.

Czerniewska, A., Brimicombe, C., Reale, A.S., Shumake-guillemot, J. and Portela, A. (2025) ‘How is maternal, newborn, and child health addressed in heat health action plans? A scoping review and content analysis’, *Journal of global health* 15: 1–16. doi: 10.7189/jogh.15.04157.

De Perez, E.C. et al. (2018) ‘Global predictability of temperature extremes’, *Environmental research letters*, 13(5). doi: 10.1088/1748-9326/aab94a.

Deivanayagam, T.A. et al. (2023) ‘Envisioning environmental equity: climate change, health, and racial justice’, *Lancet* 402(10395): 64–78. doi: 10.1016/S0140-6736(23)00919-4.

Domeisen, D.I.V. et al. (2023) ‘Prediction and projection of heatwaves’, *Nature reviews earth and environment* 4(1): 36–50. doi: 10.1038/s43017-022-00371-z.

Egerton, P. et al. (2022) ‘Early warning for all. executive action plan 2023-2027’, p. 56.

Eggeling, J., Rydenfält, C., Kingma, B., Toftum, J. and Gao, C. (2022) ‘The usability of ClimApp: a personalized thermal stress warning tool’, *Climate services* 27. doi: 10.1016/j.cliser.2022.100310.

EIMS (2025) ‘National Early Action Protocol (NEAP) for heatwave’, *Rev.*, June.

Fai, H. et al. (2026) ‘Assessing health risks of extremely hot weather and the need for enhanced heat alerts in a City with a subtropical climate’, *International Journal of Biometeorology*, 70(4), pp. 1–12. https://link.springer.com/content/pdf/10.1007/s00484-026-03155-y.pdf

Fanning, A., Mach, K.J., Cruz, M. and Clement, A.C. (2025), ‘Global metrics quantify shifts in chronic heat’, *Authorea Preprints*. https://advance.sagepub.com/doi/pdf/10.31124/advance.175696890.00368464/v1

Gasparrini, A. and Mistry, M. (2024) ‘An operational framework for real-time forecast of temperature-related excess mortality at small-area level’, *ISEE conference abstracts* 1. doi: 10.1289/isee.2024.1418.

GHHIN (2023a) ‘Heat early warning system roundtable’, February, pp. 1–12. https://heathealth.info/wp-content/uploads/Heat-Early-Warning-Systems-Roundtable-4-1.pdf

GHHIN (2023b) ‘Reporting on heatwaves and the health impacts of heat’, July, pp. 1–6. https://heathealth.info/resources/reporting-on-heatwaves-and-the-health-impacts-of-heat/

GHHIN, UNDRR, and WMO (2025), ‘An assessment of heat action plans: global standards, good practices and partnerships’, July.

Golding, B. (2022) ‘Towards the ‘perfect’ weather warning: bridging disciplinary gaps through partnership and communication’. *Springer Nature*.

Grasso, V., Crisci, A., Morabito, M., Nesi, P. and Pantaleo, G. (2017) ‘Public crowdsensing of heat waves by social media data’, *Advances in science and research* 14: 217–26. doi: 10.5194/asr-14-217-2017.

Guo, Q., Yuan, L., Ng, C.F.S. and Hashizume, M. (2024) ‘Evaluating Japan’s revised heat-health warning system in the face of recent escalating heat stress’, *Environmental research letters* 19(5). doi: 10.1088/1748-9326/ad3a81.

Hass, A.L., Runkle, J.D. and Sugg, M.M. (2021) ‘The driving influences of human perception to extreme heat: a scoping review’, *Environmental research* 197: 111173. doi: 10.1016/j.envres.2021.111173.

Heidenreich, A. (2024) ‘Individual heat adaptation: analyzing risk communication, warnings, heat risk perception, and protective behavior in three German cities’, *Risk analysis* 44: 1788–808. doi: 10.1111/risa.14278.

Hess, J.J. and Ebi, K.L. (2016) ‘Iterative management of heat early warning systems in a changing climate’, *Annals of the New York academy of sciences* 1382(1): 21–30. doi: 10.1111/nyas.13258.

Holmberg, E., Quijal-Zamorano, M., Ballester, J. and Messori, G. (2025) ‘Skillful heat-related mortality forecasting during recent deadly European summers’, *PNAS* 122 (41). doi: https://doi.org/10.1073/pnas.2426516122.

IPCC (2023) ‘Climate change 2023 synthesis report'. doi: 10.59327/IPCC/AR6-9789291691647.

Jay, O., Vanos, J., Gagnon, D. and Tartarini, F. (2025) ‘To save lives in heatwaves, focus on how human bodies work’, *Nature* 644 (8075): 35–8. doi: 10.1038/d41586-025-02461-6.

Kacker, K., Srivastava, P. and Mukherjee, M., 2025. ‘Personalized heat stress early warning system for an urban area’. *Environment International,* 199. DOI: 10.1016/j.envint.2025.109507.

Kalkstein, L.S., Jamason, P.F., Greene, J.S., Libby, J. and Robinson, L. (1996) ‘The Philadelphia hot weather-health watch/warning system: development and application, summer 1995’, *Bulletin of the American meteorological society* 77(7): 1519–28. doi: 10.1175/1520-0477(1996)077<1519:TPHWHW>2.0.CO;2.

Khan, R., Subedi, A., Grunholz, M. and Mistry, M. (2025) *Dhangadhi heat action plan 2025*, Red Cross Red Crescent Climate Centre. https://www.climatecentre.org/wp-content/uploads/Dhangadhi-Heat-Action-Plan-2025.pdf

Kingma, B.R.M. et al. (2021) ‘Climapp—integrating personal factors with weather forecasts for individualised warning and guidance on thermal stress’, *International journal of environmental research and public health* 18(21): 1–26. doi: 10.3390/ijerph182111317.

Kotharkar, R. and Ghosh, A. (2022) ‘Progress in extreme heat management and warning systems: A systematic review of heat-health action plans (1995-2020)’, *Sustainable cities and society* 76: 103487. doi: 10.1016/j.scs.2021.103487.

Lagadec, P. (2004) ‘Understanding the French 2003 heat wave experience: beyond the heat, a multi-layered challenge’, *Journal of contingencies and crisis management* 12(4): 160–9. doi: 10.1111/j.0966-0879.2004.00446.x.

Leite, A., Santos, A.J., Silva, S., Nunes, B., Mexia, R., and Rodrigues, A.P. (2020) ‘Assessing the use and understanding of the Portuguese heat-health warning system (ICARO)’, *Journal of public health (United Kingdom)* 42(2): 395–402. doi: 10.1093/pubmed/fdaa029.

Lo, Y.T.E. et al. (2023) ‘Optimal heat stress metric for modelling heat-related mortality varies from country to country’, *International journal of climatology* 43(12): 5553–68. doi: 10.1002/joc.8160.

Lusambili, A. et al. (2024) ‘Community perspectives of heat and weather warnings for pregnant and postpartum women in Kilifi, Kenya’, *PLOS one*. doi: 10.1371/journal.pone.0313781.

MacClune, K., Rubenstein, N., Norton, R., Pestalozzi, A. and Keating, A. (2026) *Understanding extreme heat and entry points for action*, Australian Red Cross and Zurich Insurance Ltd, Sydney.

Matthies, F., Bickler, G., Marin, N. and Hales, S. (2008) *Heat-health action plans – guidance*, WHO Europe. https://www.who.int/publications/i/item/9789289071918

Matzarakis, A. and Giannaros, C., (2025). ‘Toward the Next-Generation of Heat-Health Warning Systems and Action Plans’, *Atmosphere*, 16(8), pp. 14–19. DOI: https://doi.org/10.3390/atmos16080938

McGregor, G. (2024) ‘Heatwave’s. In *Heatwaves: Causes, Consequences and Responses*, pp. 3-28. Cham: Springer International Publishing. https://link.springer.com/chapter/10.1007/978-3-031-69906-1_1

McGregor, G.R., Bessemoulin, P., Ebi, K.L. and Menne, B. eds., (2015) ‘Heatwaves and health: guidance on warning-system development’ (No. 1142). Geneva, Switzerland: World Meteorological Organization.

McLoughlin, N., Howarth, C. and Shreedhar, G. (2023) ‘Changing behavioral responses to heat risk in a warming world: How can communication approaches be improved?’, *Wiley interdisciplinary reviews: climate change* 14(2): 1–19. doi: 10.1002/wcc.819.

Nairn, J. and Mason, S.J. (2025) ‘Extreme heat and heatwaves: hazard awareness and impact mitigation’, *Lancet planetary health*: 101282. doi: 10.1016/j.lanplh.2025.06.006.

Nunes, A.R. (2024) ‘Heatwaves: the silent killers of public health’, *Disaster medicine and public health preparedness*: 11069. doi: https://doi.org/10.1017/dmp.2024.144.

Oberai, et al. (2025) ‘A digital heat early warning system for older adults,’ *npj Digital Medicine*: 1-12. doi: 10.1038/s41746-025-01505-5.

O'Connor, F.K. et al. (2025) 'Promoting targeted heat early warning systems for at-risk populations', *Nature climate change* 15(8):806-8. doi: 10.1038/s41558-025-02374-2.

O'Neill, S. et al. (2023) 'Visual portrayals of fun in the sun in European news outlets misrepresent heatwave risks', *Geographical journal* 189(1): 90–103. doi: 10.1111/geoj.12487.

OCHA (2022) *Extreme heat: preparing for the heatwaves of the future*. https://www.unocha.org/publications/report/world/extreme-heat-preparing-heatwaves-future-october-2022

Oka, K., Honda, Y. and Hijioka, Y. (2023) 'Launching criteria of 'heatstroke alert' in Japan according to regionality and age group', *Environmental research communications*, 5(2). doi: 10.1088/2515-7620/acac03.

Olson, M. K., Sutton, J., & Waugh, N. (2023) 'Tweeting the heat: An analysis of the National Weather Service's approach to extreme heat communication on twitter', *Weather, Climate, and Society*, 15(4), 963-977.

Otero, N., Pelivan, I., Fitoz, B., Luterbacher, J., Kuglitsch, M.M. and Ma, J. (2026) 'Advancing early warning systems: AI applications , challenges and emerging insights', *Environmental research letters* 21. doi: 10.1088/1748-9326/ae5f7f.

Ouyang, M., Lin, N. and Gori, A. (2025) 'Hurricane Ida' s blackout-heatwave compound risk in a changing climate', *Nature communications* 16: 4533. doi: 10.1038/s41467-025-59737-8.

Painter, P., Semmens, K., Maxfield, K., Cattoën, C. and Carr, R.H. (2025) 'Designing effective flood early warning systems: a review of barriers, best practices, and key characteristics', *Journal of flood risk management* 18(4). doi: 10.1111/jfr3.70145.

Pascal, M. et al. (2006) 'France's heat health watch warning system', *International journal of biometeorology* 50(3): 144–53. doi: 10.1007/s00484-005-0003-x.

Pascal, M., Laaidi, K. and Fouillet, A. (2012) 'How to use near real-time health indicators to support decision-making during a heat wave: the example of the French heat wave warning', *PLoS currents* 16(4): 1–14. doi: 10.1371/4f83ebf72317d.

Peerlings, E.E.M. and Steeneveld, G.-J. (2025) 'Unravelling indoor temperature response to summer heat through long-term crowdsourced observations in Dutch residences', *Quarterly journal of the royal meteorological society* 152:(775): e70053. doi: 10.1002/qj.70053.

Pereira Marghidan, C., Nairn, J., Blanford, J., van Aalst, M. and Mistry, M.N. (2025) 'Untangling the fragmented landscape of extreme heat services and warning systems', *Environmental research letters*, 20(10). doi: 10.1088/1748-9326/adfe00.

Pereira Marghidan, C., Sluijter, R., Blanford, J., Homan, H., Siegmund, P. and van Aalst, M. (2026) 'The evolution of the Dutch heat early warning system (2007–2025)'.

Phung, V.L.H. et al. (2025) 'Determining location-specific thresholds for heat warning systems to mitigate heatstroke mortality in Japan', *Environment & health (Washington, D.C.)* 4(1):144-53. doi: 10.1021/envhealth.5c00113.

Podesta, M., Beswick, A. and Mehryar, S. (2026) *Towards an extreme heat governance framework: literature review*, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London.

Potter, S., Harrison, S. and Kreft, P. (2021) 'The benefits and challenges of implementing impact-based severe weather warning systems: perspectives of weather, flood, and emergency management personnel', *Weather, climate, and society* 13(2): 303–14. doi: 10.1175/wcas-d-20-0110.1.

Red Cross Red Crescent Climate Centre (2023) *Understanding the compound risk of heat, humidity and air pollution on human health: a scoping review*, September. https://www.climatecentre.org/wp-content/uploads/RCCC-Heat-Humidity-AP-Scoping-Review-Final-4.pdf

Romanello, M. et al. (2024) 'Review: the 2024 report of the Lancet countdown on health and climate change: facing record-breaking threats from delayed action', *Lancet* 6736(24). doi: 10.1016/S0140-6736(24)01822-1.

Royé, D. et al. (2026) 'Rethinking early warning systems for the health effects of extreme heat', *Nature health* 1: 6–8. doi: 10.1038/s44360-025-00004-x.

Sen, S., Cartagena, O., Khan, R. and Powell, R. (2022) *Heat communication guide for the cities in South Asia*, Red Cross Red Crescent Climate Centre. https://cdkn.org/sites/default/files/2022-04/RCCC%20Guidance%20Note-Heat%20Comm%20Plan.pdf

Singh, R. et al. (2025) *Double jeopardy: addressing compound flood and heatwave events Double jeopardy: Addressing compound flood and heatwave*, January. https://zcralliance.org/resources/item/double-jeopardy-addressing-compound-flood-and-heatwave-events/

SOFF (2023) 'SOFF operational manual'. *Systematic Operations Financing Facility*. https://un-soff.org/document/soff-operations-manual/

Start Network (2022) Pakistan heatwave model, March. https://startnetwork.org/learn-change/resources/library/pakistan-heatwave-model

Syed, S., O'Sullivan, T.L., and Phillips, K.P. (2022) 'Extreme heat and pregnancy outcomes: a scoping review of the epidemiological evidence', *International journal of environmental research and public health* 19(4). doi: 10.3390/ijerph19042412.

Tang, C. (2022) '"Amber alert" or "heatwave warning": the role of linguistic framing in mediating understandings of early warning messages about heatwaves and cold spells', *Applied linguistics* 43(2): 227–48. doi: 10.1093/applin/amab020.

Tham, S., Thompson, R., Landeg, O., Murray, K.A. and Waite, T. (2020) 'Indoor temperature and health: a global systematic review', *Public Health* 179: 9–17. doi: 10.1016/j.puhe.2019.09.005.

The Climate Studies Group Mona and The University of the West Indies (2020) 'The state of the Caribbean climate', April. DOI: https://doi.org/10.1002/JOC.2200

UNDRR (2017) 'The Sendai framework terminology on disaster risk reduction. Early warning system'. https://www.undrr.org/terminology/early-warning-system.

USAID (2024) 'Case study: climate information services for health systems strengthening a health early warning system to reduce extreme heat impacts in Senegal', June. https://www.preventionweb.net/publication/climate-information-services-health-systems-strengthening

Van Daalen, K.R. et al. (2022) 'Extreme events and gender-based violence : a mixed-methods systematic review', *Lancet planetary health* 6(6): e504–23. doi: 10.1016/S2542-5196(22)00088-2.

Vandermolen, K., Kimutis, N. and Hatchett, B.J. (2022) 'Recommendations for increasing the reach and effectiveness of heat risk education and warning messaging', *International journal of disaster risk reduction* 82: 103288. doi: 10.1016/j.ijdrr.2022.103288.

WHO (2024) *All for health, health for all: investment case 2025-2028*. https://www.who.int/publications/i/item/9789240095403

WHO Regional Office for Europe (2021) *Heat and health in the WHO European Region: updated evidence for effective prevention*. https://www.who.int/europe/publications/i/item/9789289055406

Wilson, A.J. et al. (2024) 'Heat disproportionately kills young people : Evidence from wet-bulb temperature in Mexico', *Science advances* 3367: 1–9. doi: 10.1126/sciadv.adq3367.

WMO (2021) *WMO guidelines on multi-hazard impact-based forecast and warning services*, no. 1150. https://etrp.wmo.int/pluginfile.php/42254/mod_page/content/18/WMO-1150_multihazard-guidelines_en.pdf

WMO (2023) *2023 state of climate services: health*. WMO. https://wmo.int/resources/publication-series/state-of-climate-services/2023-state-of-climate-services-health

WMO (2025) *Extreme heat risk governance framework and toolkit*, WMO, Geneva. https://www.undrr.org/publication/documents-and-publications/extreme-heat-risk-governance-framework-and-toolkit

WMO and FAO (2025) *Extreme heat and agriculture report*. https://openknowledge.fao.org/items/436c55ae-6662-4f7e-9fac-0588db782f5e

World Meteorological Organization (2021) *Guide to instruments and methods of observation. volume IV: space-based observations*, no. 8. https://community.wmo.int/site/knowledge-hub/programmes-and-initiatives/instruments-and-methods-of-observation-programme-imop/guide-instruments-and-methods-of-observation-wmo-no-8

Yoo, J., Zuccarina, C. and Wesley Ralston, J. (2023) *Heat health warning systems: progress, success stories and challenges*. https://www.graduateinstitute.ch/sites/internet/files/2024-01/Final%20Report%20ARP%205_04_Heat%20Health%20Warning%20Systems-%20Progress%2C%20Success%20Stories%20and%20Challenges_Jieun%20Yoo%2C%20Clara%20Zuccarino%2C%20Jack%20Wesley%20Ralston%20.docx%20-%20Clara%20Zuccarino.pdf

Youds L. and REAP Early Warning Systems Working Group (2025) *Artificial intelligence and early warning systems: promise, peril, and the path forward*. REAP. https://www.early-action-reap.org/blog/artificial-intelligence-and-early-warning-systems-promise-peril-and-path-forward

Young, J.C., Arthur, R., Spruce, M. and Williams, H.T.P. (2021) 'Social sensing of heatwaves', *Sensors* 21(11): 1–16. doi: 10.3390/s21113717.

Zamorano, M.Q. et al. (2024) 'Forecast skill assessment of an operational continental health forecasting system: new avenues for health early warning systems', *Science advances* 10: 1–9. doi: 10.1126/sciadv.ado5286.

Zhang, Z., Fischer, E., Zscheischler, J. and Engelke, S. (2025) 'Numerical models outperform AI weather forecasts of record-breaking extremes', pp. 1–41. *arXiv preprint arXiv:2508.15724.*

Zhao, Q. et al. (2021) 'Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study', *Lancet planetary health* 5(7): e415–25. doi: 10.1016/S2542-5196(21)00081-4.