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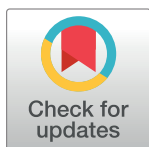
REVIEW

Preventing heat-related deaths: The urgent need for a global early warning system for heat

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Abstract

Heatwaves are the deadliest weather hazard and people and societies across the world continue to suffer from heat-related impacts. Future climate projections show a troubling increase in cross-sectoral impacts including health and economic risk presented by heatwaves. Many weather hazards such as floods and droughts already have a type of Early Warning System (EWS) or Global Alert System, but a global heat early warning system currently does not exist. An accurate heat EWS can save lives and can promote heat adaptation across society. Here, we (1) explore the history of Early Warning Systems as framed using the Disaster Risk Reduction paradigms and (2) identify potential barriers to an integrated Global Heat Early Warning system. Finally, we discuss what we have learned from history and the identified current barriers and outline a vision of a Global Heat Early Warning system around four key themes, incorporating systems for low-, middle-, and high-income countries and requiring cross-sectoral, cross-government, and interdisciplinary collaboration.

1. Introduction

Heatwaves are the deadliest weather hazard linked to climate change [1]. Currently, five billion people live in regions where weather forecasts can accurately predict heat extremes [2]. Yet, few countries have Early Warning Systems specifically designed for heat [3]. International bodies, including the World Health Organization (WHO) and the World Meteorological Organisation (WMO) set a mandate to develop Early Warning Systems for heat after the deadly European Heatwave in 2003 killed over 50,000 people [4,5]. In 2022, the WMO at COP27 and the Sendai Risk Reduction Framework mandated an 'Early Warnings for All' framework, in which 4 main weather hazards (i.e., storms, floods, droughts, and heatwaves) must be covered by a global Early Warning System by 2027 [6,7]. In this paper, we advocate

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that a people-centred, multi-hazard early warning system is a cost-effective way to enhance risk reduction and adaptation measures to increasing weather impacts due to climate change [8]. The emergent collective effort around developing comprehensive Early Warning Systems has been dubbed a global imperative where the “time is ripe for bold action” [9].

The United Nations Office for Disaster Risk Reduction (UNDRR) has defined an Early Warning System (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*”[10]. EWSs exist along a continuum, from a linear systematic approach where a weather forecasting agency issues a warning to a fully integrated early warning system, whereby cross-sectoral collaboration is employed, and other actors assist to issue a warning and put in place risk reduction strategies [9]. At a global scale, different types of EWSs exist for major weather hazards such as droughts and fluvial flooding, but no global early warning system exists yet for heatwaves [11].

At present, various countries have already implemented heat-health warnings and action plans tailored to their specific climates. For instance, several European nations have established national heat-health warning systems [12], while China has developed and enacted a heatwave early warning system to mitigate health hazards associated with extreme temperatures [13]. Additionally, collaborative efforts by the WHO/WMO are underway to enhance guidance on heatwave and heat health early warning systems, through the Global Heat Health Information Network (GHHIN). Despite these commendable national and regional initiatives, there remains a critical gap in global coordination and gaps for sectors outside of health [14].

Advocating for a comprehensive global early warning system is imperative. Unlike regional or national systems, a global approach enables seamless surveillance of heat risks worldwide. It facilitates the adoption of standardized technical frameworks adaptable to diverse local contexts, fostering global consistency while accommodating regional nuances. A global heat early warning system is necessary to achieve the United Nation's ‘Early warnings for All’ initiative by 2027, because more frequent and intense extreme heat events (including heatwaves) driven by a changing climate already are disproportionately impacting an increasing number of people worldwide. Urban populations are particularly vulnerable because of the urban heat island effect[15]. While the Sendai Framework for the Disaster Risk Reduction agenda currently recognizes climate change as an important driver of disaster risk, extreme heat has only recently emerged as a priority for action [14,16].

In this paper, we explore challenges in operationalizing a global early warning system for heat. We present the history of EWSs as framed using Disaster Risk Reduction paradigms and then identify key barriers that exist to a global early warning system approach for heat. Finally, we outline a vision for an effective global early warning system for heat for the health sector and beyond.

2. History of early warning systems

One of the first global EWSs was the Famine Early Warning Systems Network (FEWS NET), developed in the 1980s to reduce the risk of famine across nations in the Horn of Africa [17]. Since the early inception, EWSs have shifted to include quick onset and, more recently, slow onset weather hazards to provide timely early warnings containing information on the emerging hazard, risks, and critical vulnerability for the impacted communities. Individual EWSs exist along a continuum, from a linear systematic early warning system where a warning is issued by a weather forecasting agency to an integrated early warning system where cross-sectoral collaboration is employed to issue a warning and implement place-based risk reduction

and adaptive strategies [9]. Advanced EWSs are considered a climate service, that is, the provision of climate information to assist decision-making and reduce harm [18]. EWSs are an inherent part of the social, cultural and political process. They serve as an embedded component in a community, providing early warning of impending harm from a hazard, as well as a means to raise awareness about a hazard, to promote training for disaster risk reduction and response, to collect baseline data, and to characterize a community's hazards, vulnerabilities, and inherent risks [19].

The concept of early warning is not new and has a long history, which is important to consider when reflecting on potential barriers and enhancements for operationalizing an EWS for extreme heat. In [Box 1](#), the history of early warning systems is briefly outlined using the framing provided in [9].

Box 1. The history of EWSs [20–32]

History of Early Warning Systems

Pre-science early warning systems (BCE):In the era prior to scientific understanding, societies and cultures understood disasters and risk through stories passed down as myths[20]. This is also sometimes tied to an extreme fatalist view of the world where disasters are seen as an act of divine beings, instead of the interactions of nature with human society [32].

Ad hoc science-based early warning systems (AD to 1755): This era includes signals from nature that were understood by societies to indicate a certain hazard was about to occur. For example, frogs are suggested to leave an area prior to a volcanic eruption, or the idea that cows lie down before it rains [21,22]. Pre-science and ad hoc science fit within the paradigm of understanding disasters prior to the Lisbon Earthquake of 1755, which is attributed to being the first 'modern' disaster with an emergency response [23].

Systematic end-to-end early warning systems (1980s to 1990s):This era is characterised by an intersecting set of core elements that involve 1) monitoring of hazard risks, 2) forecasting meaningful warnings in response to hazard threat issued to sectors, 3) responsible agencies, namely weather services, are expected to issue warnings and communicate actionable information to at risk communities [24]. It can be argued that most operational early warning systems in place now are still systematic end-to-end early warning systems because the responsibility is often placed on the weather service agencies alone. This fits within the Disaster Risk Reduction paradigms that exist for resilience and sustainability, the idea of community and political economy that developed from the 1980s to the 1990s[25–28].

Integrated Early Warning System (2000s to present): In this era in response to the move towards a participatory approach to disaster risk reduction, there is collaboration across sectors on warnings and what resources and infrastructure is needed to dissemination and put in place preparedness [28,29]. Integrated EWSS should acknowledge people's interaction within the environment, including adaptive capacity and their stories as a key element to reducing risk through an early warning system [24,30]. These systems fit within the move in the humanitarian sector towards anticipatory action [31]. Integrated Early Warning Systems have four main elements as outlined in [Fig 1](#): Risk Knowledge, Response Capability, Monitoring and Warning and Dissemination and Communication.

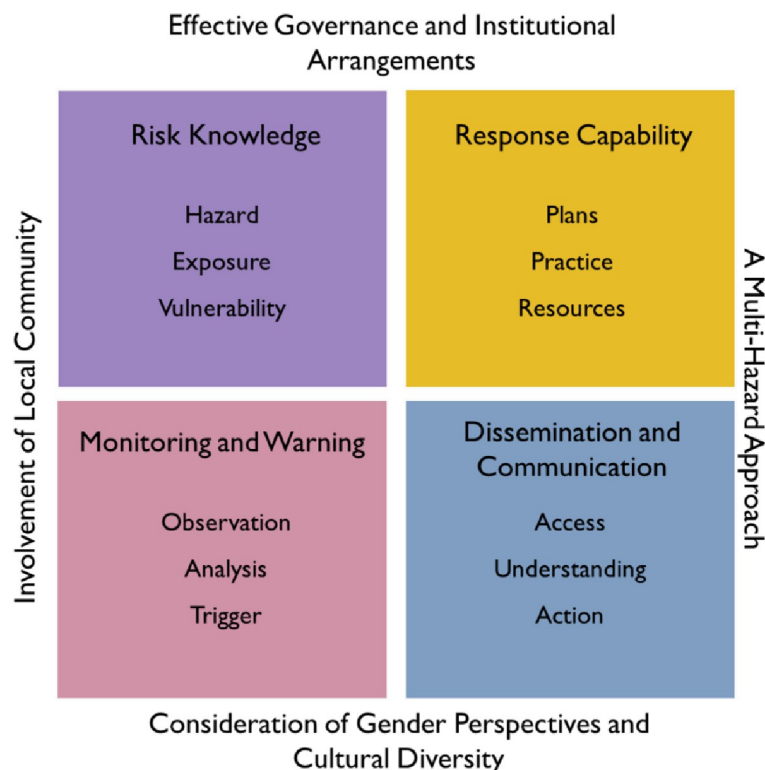


Fig 1. The current paradigm of early warning systems as set out by climate risk and early warning systems.
Adapted from [9].

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3. Barriers to a global heat early warning system

In this section, we outline the potential for a global heat early warning system in terms of the core components required in an integrated early warning system paradigm and identify key technical barriers to operationalizing an effective system (Fig 1).

Risk Knowledge

A central limitation for the implementation of a global heat EWS is that currently there is not a globally agreed upon definition of hazardous extreme heat nor heatwaves [33]. The World Meteorological Organisation (WMO) has put forth a draft global definition that broadly characterises a heatwave as “a period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds” [5]. Locally, defining a heatwave is a barrier to early warning systems because there are physiological, cultural, organisational, and regional climate differences that influence the thermal experience, expectation, perception, and acclimatisation of a population and the available infrastructure in the detection of a heatwave [34]. Defining extreme heat and heatwaves presents an important challenge for tracking the health impacts of heat within and across low-, middle-, and high-income nations. In addition, the definition of a heatwave does not always capture the impacts of heat on human health and wellbeing, in part because of the differences amongst the meteorological services and research community in measuring heat (e.g. a heatwave is a meteorological definition and heat stress is a person-specific physiological heat load phenomenon) [34].

Prior studies have compared different definitions of heatwaves and thermal comfort and demonstrated varying impacts based on the definition or index used [35–37]. These differences translate into moving targets for identifying health risk levels in vulnerable subgroups and for informing actionable heat risk thresholds for an EWS [38]. In the absence of agreed upon and actionable heat risk thresholds, it is difficult to assess the effectiveness of an EWS and to build capacity at the local and national level to achieve equitable climate adaptation approaches and policies to safeguard against extreme heat. Another important consideration is that vulnerability is often conceptualised within an early warning system or disaster risk reduction framework as a simplified, static problem [24,27]. Indeed, there is a trade-off between the need for clear communication of potential impacts from heat exposure and the fact that a single metric EWS may overly simplify the impact of extreme heat across diverse geographies and communities [34].

While anybody can be vulnerable to the hazard of extreme heat, vulnerability changes based on age, life stage, and health and heat acclimatisation status, and place-based determinants like urban setting, neighbourhood disadvantage, access to greenspace, and affordable housing [39–41]. Emerging research has also highlighted heat vulnerability during the sensitive periods of pregnancy and childhood [42,43]. Prenatal exposure to acute or prolonged periods of extreme heat has been linked with excess risk of preterm birth, hypertensive disorders of pregnancy (e.g., preeclampsia), gestational diabetes, cardiac events, extended labour, and haemorrhage around the time of childbirth [44]. Additionally, heat exposure in utero has been associated with adverse neonatal health outcomes including low-birth weight, stillbirth, congenital abnormalities; these conditions also have a high potential to result in adult conditions later in life [45–48]. More research examining heat impact thresholds for increased vulnerability and adverse health impacts during pregnancy and early childhood is needed.

In addition to physiologic vulnerability, social vulnerability or a lack of adaptive capacity in which highly vulnerable persons do not have access to the resources or the ability to escape the heat, a broader adaptive capacity influences the level of vulnerability and heat impacts that an individual within a given society experiences (50). Adaptive capacity refers to the capacity of human or natural systems to adjust to potential damage, to take advantage of opportunities, or to respond to consequences [49]. In human systems, adaptive capacity is influenced by the ability of social institutions and networks to learn and reorganise in the face of disasters, adjust decision-making, as well as by the ability of existing power structures to respond and consider the needs of different stakeholder groups [50], in particularly those who are the most vulnerable or the first and worst impacted [51]. Other built environment factors and a push for more sustainable and resilient buildings or more intentional community design practices are needed to reduce population vulnerability to heat [14].

Finally, both the physical dynamics of extreme heat and the implications for human physiology are complex and poorly understood. This limited understanding is in part due to a lack of a robust historical record of weather observations for large parts of the [52]. In terms of impacts, there is disagreement between epidemiological research, which suggests humidity is not important when assessing heat impacts [53], and physiological research that suggests humidity is key [54]. Finally, there is a bias in the literature towards studies assessing the relationship between extreme heat and health outcomes in North America and Europe, while other regions have received more limited attention [54,55].

Monitoring and prediction for robust warnings

For accurate warnings to be made on a technical basis, observations are a crucial part of numerical weather prediction. Heatwave impacts tend to be under-reported in official

meteorological reports and in EM-DAT, the emergency events disaster database [11]. Currently, there is a lack of long-term data recording the frequency, duration, intensity, and the impacts of heatwaves that occur globally, with the exception of the US, who track when a heatwave warning is issued state-by-state. For the African continent, official disaster records contain fewer heatwaves than seen in evaluated historical climate records since at least the 1990s [56]. This underreporting across Africa is due to a lack of station data—there are only 200 weather stations with a reliable temperature reporting record [52]. In addition, nearly 4 billion people worldwide live more than 25 km away from a reliable station [57]. Troublingly, climate reanalysis products of temperature not only differ substantially over large areas, but when assessing average temperatures, they reveal vastly different patterns of seasonality for extreme heat [58].

Nonetheless, in recent years, there has been a move towards implementing more complex heat stress and thermal comfort indices to project the health impacts of heatwaves [34]. There is not yet a consensus built around heat stress indices and thermal comfort and this is an area that would benefit from joint multi-disciplinary efforts between the health and climate science research community to build more consensus on identifying the leading extreme heat indicators and thermal comfort indices [54,59]. There is also a global data gap in solar radiation observations that are relevant to human heat exchange with the environment [60,61]. Observations are needed to ensure robust and accurate numerical weather and climate heat risk predictions.

Despite the limited monitoring for large parts of the globe, most regions exhibit a potential for advance warnings for the impacted population, based on the capacity to make skilful temperature forecasts, often on timescales of several weeks prior to a heatwave event [62,63]. Heat extremes are the most predictable natural hazard, for example in comparison to cold or precipitation extremes [62,64,65]. While the exact onset and duration of heatwaves is more difficult to predict, the tendency towards extreme temperatures can often be predicted 3–4 weeks ahead of the heatwave onset [66]. Data science-based methods are increasingly used to extend skilful heatwave predictions beyond the current predictability limits [67–69]. However, successful weekly or monthly predictions are not yet sufficiently used to issue heat warnings. The effectiveness of such warnings in addition relies on the existence of heat-health action plans at the national or local level [70]. Such plans are increasingly used in places that have previously experienced the devastating impacts of heat extremes and the associated mortality, but we argue for a more proactive approach to heat action planning before a deadly heatwave event occurs [3].

Response capacity

Health leaders have a unique opportunity to play a critical role in raising awareness and motivating local action and policies that reduce the impact of climate change on health given the significant contribution of the changing climate to population morbidity and mortality [71,72]. In general, there is a lack of awareness among hospital and public health decision-makers concerning the health impacts of climate change stressors like extreme heat [71,73]. There are numerous barriers to engaging health care leaders, including competing priorities with more urgent health threats (e.g. global COVID-19 pandemic), understaffing, and a general lack of capacity within the public health workforce, institutional support for prioritising extreme heat, and sustained funding for developing targeted interventions [74–77].

A key challenge to a global heatwave early warning system from the health sector perspective are the limited resources available for implementation of effective and evidence-based heat prevention and mitigation measures. Heatwaves are often regarded as an invisible health risk within international climate policy; therefore there is currently a lack of policy and legislation

to support the development of a global EWS [11,14]. Heatwave response and preparedness efforts have been historically siloed to the health sector, whereas extreme heat also is a massive infrastructure challenge [14,78]. It is important to highlight that other sectors are also impacted by heat, including forestry and agriculture, education, key infrastructure across the built environment, energy supply and demand and transportation [63].

Dissemination and communication

Effective, timely, and targeted communication with embedded heat prevention strategies is a cornerstone of a successful EWS. Heatwaves are under-reported in the English Language media in comparison to other weather hazards [79], indicating low perceived risk or societal recognition that heatwaves pose a persistent and deadly health threat [80]. For example, older adults in the UK generally perceive themselves as less vulnerable than they are categorised under the country's heat-health plan, hindering their likelihood to use heat prevention or adaptation measures to reduce personal exposure to extreme heat [81]. A recent study found that heat action in Germany was most effective if a warning was accompanied by a type of adaptation suggestion [82].

More research is needed to understand how to improve effective and targeted communication to foster adherence to EWSs, particularly around what messages work best for vulnerable subgroups [82]. One strategy involves framing the climate crisis as a public health issue and recruiting health professionals as trusted health messengers in their community to raise awareness about heat risks to health [83]. Statistics should be paired with locally appropriate personal and cultural narratives to showcase that climate change effects are happening now and that heatwaves are worsening. A concerted effort within the research community has to be made to involve impacted communities in co-creating targeted messages that link risk communication with personally achievable adaptation strategies [84].

4. State-of-the-art in current heat early warning systems

To help outline a vision for effective global heat early warnings, we provide an overview of the available state-of-the-art and effective strategies that are currently employed by heat-health early warnings within a range of countries. In the framework of a heat-health warning system, many countries issue forecasts of anticipated increases in mortality or hospital admissions to relevant stakeholders [12,70]. This is the case for example in Portugal, which has had one of the longest running heat-health early warning systems in Europe, where warning reports have been issued daily in Lisbon since 1999. A recent study interviewed users of these reports and found that despite presentation being adequate and the information being useful, the communication between users and those issuing reports could be improved [85]. This finding highlights a key recommendation to operationalizing a heat EWS in which meteorological services must work closely with end users and practitioners who rely on these reports for on the ground decision-making.

Another essential component of an EWS is that relevant government departments work together to coordinate warnings and heat-health planning efforts. One example of this is the UK, where the heat-health early warning system is under the remit of the UK health security agency (UKHSA) but relies on the forecasts from the UK Met Office [86,87]. The heat-health plan uses different thresholds from that of meteorological heatwaves and key stakeholders and vulnerable groups identified and contacted by the UKHSA. Each year, heat period mortality reports are issued by the UKHSA and the UK Met Office and UKHSA jointly update the heat-health plans based on changes in research and UK climate conditions [86,87].

Another example for a heat-health early warning system is that of France. It has been running operationally since 2004 (following the extreme mortality during the 2003 heatwave) and issues warnings based on temperature, whilst providing information about other aspects of heat, such as relative humidity [88]. Dissemination and communication for heat includes adverts on French television channels and key messages about heat [88]. In addition, Italy has an early warning system that covers different scales from the national to the local level through a number of communication methods including a mobile application [89]. The country links the high temperature data with daily almost real-time indications of mortality and individual visits to emergency departments in hospitals to further inform warnings [89].

There are a few countries and regions that are using heat indices in their heat-health early warning systems. One example is the country of Senegal, where the heat-health EWS was funded by NOAA's National Weather Service (NWS) in association with the Agence Nationale de l'Aviation Civile et de la Météorologie and the Ministry of Health. This EWS and issued warnings rely on the heat index, a metric that is also used in the US to provide heat-health warnings [90]. Another example is Australia, which makes use of the Extreme Heat Factor (EHF) metric, a way to use dry bulb temperature and incorporate the influence of adaptive capacity. Further work is ongoing in Australia to incorporate humidity into their heat-health warning system to complement the EHF [91].

The Red Cross Climate Centre has worked with several countries and regions in recent years to develop anticipatory action plans for heat [31]. In Vietnam in 2018, a 6-day advance forecast using a heat index and forecast-based financing (i.e. where humanitarian and government funds are made available in advance of a hazard) allowed for the opening of cooling centres and buses to previously identified geographically vulnerable hotspots. Volunteers are strategically stationed in these hotspots to hand out water and wet towels, while also communicating targeted heat prevention messages [92]. An evaluation of the interventions found that many residents welcomed the cooling centres and buses and wanted to see the scheme continued; government ministries are in discussions on how to expand the approach to other hazards [92].

5. A vision for effective global heat early warnings

Our vision for a successful Global Heat Early Warning system recognizes the processes outlined in Fig 1 as key components of any climate service, while also acknowledging foundational barriers that must be addressed to extend beyond the current state-of-the-art in country-wide and regional heat-health early warning systems. A global early warning system allows for warning and monitoring using a standard set of metrics and definitions. Such a system can further be used to support national-led efforts, like in the case of FEWS NET and UN monitoring such as the Sustainable Development Goals, where national indicators feedback to the global level.

A successful warning system includes multi-sectoral cooperation that integrates the public health sector and meteorological services alongside the food and agriculture, manufacturing, energy, information technology, financial, transportation sectors and beyond. Barriers will be critical to successful warnings implementation. Such persistent barriers and shortcomings of current heat surveillance, warning, and prevention strategies have been exemplified by the lack of preparedness even among the wealthiest countries during the recent Pacific Northwest Heatwave 2021 or the European Heat Summer 2022 (37,92).

Our vision builds upon existing processes that take place within UN agencies for monitoring and prevention, such as the Sustainable Development Goals (93) and seeks to pool the work and lessons learned of many countries, some of which have been discussed above, that

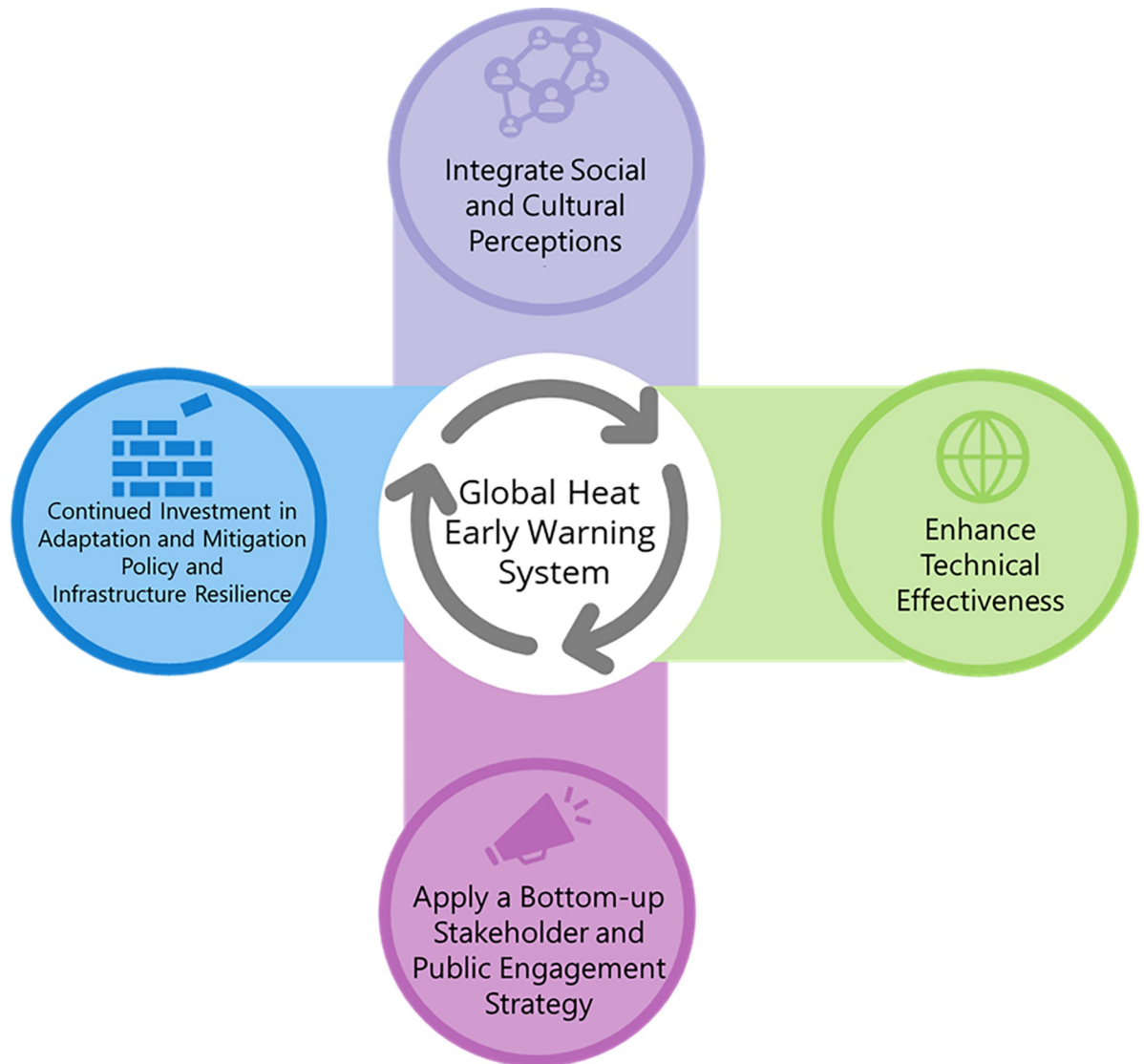


Fig 2. A 21st Century schematic of a Global Heat Early Warning system: Key thematic areas mapped upon the original early warning system schematic created by Basher et al., 2006.

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already have an operational heat-health early warning system or heatwave early warning systems in place [12]. Below, we map key thematic areas that must be addressed when developing a global heat early warning system (Fig 2), all of which can be extended to a multi-hazard framework:

1. **Integrate Social and Cultural Perceptions:** *acknowledge the socio-cultural factors that shape heat awareness, perception of risks, protective behaviours, and available adaptive strategies and provide science-based warnings and targeted response communication in the lived experience of impacted populations and the needs of local decision-makers.*
2. **Enhance Technical Effectiveness:** *embed local observations and impact knowledge in the development of skilful forecasts for a heatwave to improve the effectiveness of local and regional forecasts on a global scale.*

3. ***Apply a Bottom-up Stakeholder and Public Engagement Strategy:*** requires community-based input into the development and evaluation of adaptive messaging and requires targeted engagement with all parts of society and key stakeholders.
4. ***Continued Investment in Adaptation and Mitigation Policy and Infrastructure Resilience:*** Investment in policy and infrastructure resilience and mainstreaming of early warning systems with other intersections in parts of policy and highlight the co-benefits of early warning systems for climate action.

While new visions of a Global Heat Early Warning System do exist in the literature (e.g. for example, [93], much of the literature frames a heat-health early warning system in a way that limits heat hazards only to the health sector, without proper recognition and integration of other stakeholders and sectors.

We assert that the main barriers to a Global Heat Early Warning system include a limited consensus between stakeholders on the best approach to move forward together to define a heatwave, identify trigger thresholds for issuing warnings, and disseminate effective and targeted messaging to vulnerable subgroups, as well as the equitable sharing of resources and responsibility. A successful global heat EWS should start by using a range of heat metrics from successful country-wide systems, for example temperature, wet bulb globe temperature, or the universal thermal climate index and heat index. An EWS should be subject to constant improvement based on co-produced evaluation criteria across relevant government departments and international agencies. In addition, successful multi-hazard EWSs are only possible with participation across sectors, an example being FEWs NET, where there is multi-sectoral engagement and dissemination, alongside continuous monitoring and integration of relevant data for food security including staple food prices and household income [17]. EWSs as climate services should not be stand-alone and can provide impact reports that feed into the evaluation of national and international targets such as the Sustainable Development Goals. Further, EWSs are only effective when supported by adaptation policies and measures that consider the changing climate and resilient infrastructure, alongside transformative policy to reduce emissions to net zero mitigating the most extreme type of heat [14,30,52].

Conclusion

The time is now for a global heat early warning system. Historically, extreme heat has not been within the remit of disaster risk reduction or meteorological agencies, being siloed to the health sector. A global-scale heat early warning system is necessary to counter the borderless nature of heat hazards and the increase in frequency and severity of heat extremes observed and further expected in a changing climate. Despite the highlighted barriers, a global heat EWS should be achievable by 2027 under the “early warnings for all” scheme. Key components and opportunities of an operational global heat early warning system are: (1) the strategic identification of which heat indices and health indicators should be given priority within the system, (2) meaningful trigger thresholds for heat warnings at different spatial and temporal scales and across sectors, and (3) co-production of the EWS especially around communication, dissemination, and evaluation. Finally, it is crucial to note that effective early warning systems are only able to exist alongside robust infrastructure, policy and adaptation measures that can take years to decades to establish, and that are subject to changing baselines in a changing climate. These measures should be part of a systems approach to tackling the climate change emergency alongside EWSs.

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