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PERSPECTIVE

Untangling the fragmented landscape of extreme heat services and warning systems

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Abstract

Extreme heat warning systems are expanding globally, yet remain conceptually fragmented and operationally diverse. With a myriad of heat indices in use and limited guidance on their purpose or performance, countries risk adopting ineffective systems misaligned with local risks and decision-making needs. This Perspective traces the roots of this fragmentation across disciplinary, operational, and institutional lines, showing how differing approaches from health, meteorology, and climate science have led to incompatible definitions and thresholds. We then propose a clear typology of heat indices, aligned with WMO guidance: (1) temperature indicators, (2) thermal indices, and (3) heatwave intensity indices. The typology clarifies what each type measures, where it performs best, and the trade-offs involved, helping systems move toward greater transparency, coherence, and fit-for-purpose. Each type offers distinct strengths, and many countries will benefit from layered approaches that combine them. Moving toward intensity-based approaches represents a conceptual shift, from identifying hot days to quantifying the severity of heatwaves. By aligning early warning systems with this understanding, countries can improve coordination, reduce health and societal impacts, and accelerate progress under global frameworks such as the UN's Early Warnings for All initiative.

1. Introduction

The frequency, duration, intensity and spatial extent of heat extremes are rising sharply under climate change, increasing the need for climate and meteorological extreme heat services and warnings that trigger life-saving action across public health, agriculture, energy, transport and labor sectors (McGregor 2024; Brogno *et al* 2025). Currently, only 54% of meteorological services issue extreme heat warnings, highlighting the urgent need to expand systems worldwide (Kotharkar and Ghosh 2022, WMO 2023).

Among existing warning systems, the methods for monitoring and defining extreme heat vary dramatically (Casanueva *et al* 2019, Kotharkar and Ghosh 2022, McGregor 2024). While some variation is expected, the current degree of inconsistency (both in the literature and operational systems) undermines our ability to understand and respond to heat risk, and make comparisons between systems. Many systems rely on multi-day exceedance of maximum temperature, but such definitions fail to parameterize cumulative heat, a defining characteristic of heatwaves (Kotharkar and Ghosh 2022, McGregor *et al* 2024, Nairn 2021, WMO n.d.).

In this perspective, we argue for a fundamental shift in how heat-related services and warnings are conceptualized and operationalized. Today's fragmented warning landscape, shaped by diverse systems, definitions, and sectoral approaches, is weakening the effectiveness of warnings, limiting comparability of research, and hindering coordinated action across sectors and borders. We show that the choice of heat definition is foundational, where the choice of heat indices shapes how it can be monitored in space and time, including outcomes of impact assessments.

To support greater coherence and effectiveness, we propose a typology of heat indices: (1) temperature indicators, (2) thermal stress indices, and (3) heatwave intensity indices, that clarifies what each type captures, their trade-offs, and appropriate use cases. This framework can guide countries in making transparent, fit-for-purpose choices, while remaining responsive to evolving science and local needs.

By addressing these conceptual gaps, we aim to enable more consistent and impact-relevant extreme heat services and warnings, aligned with the UN's Early Warnings for All initiative, the Sendai Framework, and emerging WMO/WHO guidance. Only through shared standards and clearer principles can we scale up systems that protect lives and reduce the rising toll of extreme heat globally. To achieve this, all actors working on extreme heat services—across meteorology, public health, climate science, and disaster risk management—must collectively work toward shared principles and a clearer foundation for extreme heat services worldwide.

2. Understanding the diversity of warning systems for extreme heat

Extreme heat warning systems began to emerge globally in the late 20th century, often in response to deadly events that exposed their absence. Early systems were notably developed at the city-level, primarily driven by demand from the health sector and specifically aimed at reducing excess mortality. Examples include Philadelphia in 1995 (followed by other North American cities), Lisbon in 1999, Shanghai, Toronto, and Rome in 2001, with France launching a national system after the deadly 2003 heatwave (Kalkstein *et al* 1996, Pascal *et al* 2006, Leite *et al* 2020, Kotharkar and Ghosh 2022). After the 2003 and 2006 European heatwaves, many more European countries followed, with some basing their systems on epidemiological evidence, while others relied on climatological thresholds and temperature anomalies (Casanueva *et al* 2019). The 2010 heatwave in India and Pakistan also spurred action in South Asia. Ahmedabad became the first city in the region to develop a Heat Action Plan in 2013, later followed by the Indian Meteorological Department's development of a national heatwave warning system (Kotharkar *et al* 2022, IND, 2019). In some cases, existing warning systems were expanded to serve multiple audiences. For example, Portugal's initial heat-health warning system (ÍCARO) was developed for public health purposes (Leite *et al* 2020), while the meteorological service later added warnings based on extreme temperature thresholds (IPMA n.d.).

Today, existing systems differ widely in terms of indices, thresholds, and whether they are grounded in health outcomes or not (often referred to as hazard vs. impact-based warning systems). Much of this diversity stems from the way different disciplines have historically approached extreme heat. Health, meteorological services, and climate science communities have developed distinct indices to reflect their specific priorities. The health sector alone has produced a myriad of thermal indices (Epstein and Moran 2006, de Freitas and Grigorieva 2017), while meteorological services often responded reactively to health demands, without treating heatwaves as a core weather hazard. Climate scientists, in contrast, have focused on long-term anomalies and extreme event attribution. As a result, there is ongoing conceptual conflation between climatic temperature extremes, thermal heat as a physiological stressor, and heatwaves as an environmental meteorological phenomenon.

Warning systems have also been shaped by structural, operational, and climatic factors. Many systems emerged in response to sector-specific service demand, mostly from the health sector (leading to 'heat-health warning systems'). In some cases, systems were constrained by the technical capacity of meteorological services at the time of development; in others, by gaps in key observational or health data (McGregor *et al* 2015). Some systems evolved through iterations informed by local scientific evidence on health outcomes (e.g. Burgstall *et al* 2019) or operational experience, while others were shaped by the practices of neighboring countries. The local climate matters too; for example, systems in humid tropical regions have prioritized thermal indices that account for humidity (McGregor *et al* 2015).

While some systems have evolved over time, many remain shaped by health-specific perspectives rather than cross-sector learning. However, the choice of heat indices has profound implications for how heat is monitored and managed.

3. Why the choice of heat definition matters—both for research and operations

How extreme heat is defined is not just a technical detail, it fundamentally shapes the warning system and has far-reaching consequences for both science and practice. The choice of definition and threshold determines how heat is detected, the lead time, how far and long an event extends, timing of warnings, and thus how well-connected it is to impacts and for which sectors and population groups the information might be relevant (Becker *et al* 2022, Cvijanovic *et al* 2023). Studies have shown that estimates of heat-related mortality can vary substantially depending on the heat definition or metric used (Barnett *et al* 2010, Kent *et al* 2014, Xu *et al* 2016, Lo *et al* 2023, Guo *et al* 2024). Because different indices emphasize different aspects of extreme heat (e.g. physiological stress, statistical extremes, or multi-day persistence), they lead to inconsistent conclusions and complicate the assessment and communication of heat-related risks (Vogel *et al* 2020, Becker *et al* 2022, Brogno *et al* 2025).

Despite the critical role that heat indices play in shaping warnings and impact assessments, assumptions are often made about what specific indices capture, and their relationship to impacts, such as health outcomes, is not always well understood on a local scale (McGregor and Vanos 2018). While it is often assumed that thermal indices like Wet-Bulb Globe Temperature or the Heat Index are inherently more relevant for health, some studies challenge this assumption. While a global study found no consistent advantage of humidity-based indices over temperature alone for predicting heat-related mortality across climate types (Lo *et al* 2023), more recent evidence highlights their relevance in specific climatic contexts, especially where temperature and relative humidity are not or weakly correlated (Guo *et al* 2024). Baldwin *et al* (2023) add that the role of humidity also depends on statistical modeling assumptions and contextual factors. Further, Vanos *et al* (2020) caution that heat-health projections often rely on oversimplified human models, overlooking key factors such as exposure duration, individual physiology, clothing, and behavior. This suggests that many systems that aim to protect health may be using indices that are not well suited to local and future health risks, either because of incomplete evidence or assumptions that do not hold across all settings. Therefore, there is both a need for continued epidemiological research and tailoring and validating thresholds locally when serving health-related objectives. Recent work has highlighted the value, and complexity, of developing more personalized warning systems that reflect variations in individual exposure, vulnerability, and context (Kuras *et al* 2017, O'Connor *et al* 2025).

At the same time, the dominance of health-driven perspectives in research has strongly shaped the design of many operational systems, resulting in warnings that are typically based on either maximum temperature (T_{max}) or thermal indices (e.g. Burgstall *et al* 2019). While this health-oriented focus has generated valuable insights into mortality risk, it has left other operational needs underexplored, such as lead time, forecast skill, and relevance across sectors. This leaves trade-offs insufficiently addressed, such as between indices that are more predictive of health outcomes but have shorter lead times and may thus be less useful for anticipatory action.

The limitations of current approaches vary by region. In temperate regions, where Tmax is most commonly used, there is growing recognition of the need to move toward intensity-based metrics that measure cumulative heat (Nairn and Mason 2025). These are more aligned with multi-sectoral impacts and are also more useful for scaling warnings across regions. Emerging approaches, such as the event-based framework proposed by Lo *et al* (2021) and employed in Australia (AUS 2022), offer ways to better capture the spatial and temporal coherence of heatwaves and avoid fragmentation caused by fixed-day thresholds. They allow cumulative heat to be tracked as a continuous phenomenon, which is critical for improving the relevance of warnings across sectors and regions. In tropical settings, where heat and humidity are persistent, thermal indices may better capture heat stress, yet more research is needed to identify which metrics and extreme heat services (e.g. seasonal forecasts) best support decision-making in contexts of seasonal and chronic heat.

In the absence of clear and shared frameworks, meteorological services are left to navigate a fragmented and sometimes confusing array of indices. This has led to the continued use of legacy methods or the uncritical adoption of indices, without evaluating their suitability for local risks or users. The narrow focus on health outcomes has reinforced the use of indices optimized for detecting mortality risk, rather than those designed for broader, multi-sector operational relevance. Bridging this gap will offer an opportunity to develop more holistic and operationally useful systems that go beyond health and support multi-sector resilience.

To improve both the effectiveness and coherence of heat warning systems, there is a need to develop a clearer typology of indices and converge on a smaller set of high-impact metrics (Becker *et al* 2022, Brogno *et al* 2025). These should be chosen based on their robustness, relevance to local risks, and ability to inform decisions across sectors, aligned with the evolving UNDRR/WHO governance frameworks. National heat warning systems should operate as multi-hazard platforms that detect weather phenomena of societal concern, while enabling sector- or purpose-specific thresholds for tailored decision-making. Clarifying these roles, and ensuring local validation, can greatly enhance the credibility and usability of extreme heat services.

4. Building more coherent and scalable heat services

4.1. A typology of heat indices for extreme heat services

To help services navigate the complexity of defining and monitoring extreme heat, we propose a typology that distinguishes between three broad categories of heat indices, in line with WMO recommendations (figure 1) (unpublished). In contrast to other classifications of heat indices that have focused on the physical structure or construction of biometeorological or thermal indices (e.g. McGregor and Vanos 2018), here we organize indices according to their intended purpose: what they aim to capture and how they are typically applied in warning systems.

Each type serves different operational, sectoral, and climatological contexts, and reflects a distinct conceptual approach: Type 1 flags anomalous temperatures, Type 2 represents thermal stress, and Type 3 quantifies cumulative heatwave intensity over time. Clarifying these differences is essential to guide appropriate use, improve system coherence, and support the development of more effective, impact-based warning services. Across all three types, threshold values can be either relative (based on local climatology or percentiles) or absolute (fixed values). Cutoff values may be derived from climatological criteria or from impact data, corresponding to hazard-based and impact-based systems, respectively.

Type 1: temperature indicators: these include indicators such as daily maximum or minimum temperature. They are simple, widely available, and offer high forecast skill at relatively long lead times. As a result, they are well-suited for general public alerts, early warning lead times, and climate monitoring. They rely on standard climate services infrastructure and are easily comparable across space and time. While some temperature-based warning definitions use multi-day thresholds (e.g. several consecutive days exceeding a set temperature), these still operate as binary triggers and do not quantify cumulative excess heat or intensity beyond the threshold. As such, they capture only part of the risk (primarily statistical anomalies), and do not account for humidity, radiation, or physiological stress. Despite these limitations, they remain the dominant basis for extreme heat warnings globally due to their operational simplicity.

Type 2: thermal (heat stress) indices: indices such as the WBGT and the universal thermal climate index (UTCI) incorporate multiple meteorological variables, including temperature, humidity, solar radiation, and wind speed, to estimate the body's thermal load. These indices aim to provide a more physiologically meaningful measure of heat stress and are highly relevant for occupational safety, public health, and real-time thermal risk information (McGregor and Vanos 2018). However, they are more complex to implement in an operational alert system: difficult for a user to interpret (as their units/scales are not comparable to each other and to temperature),

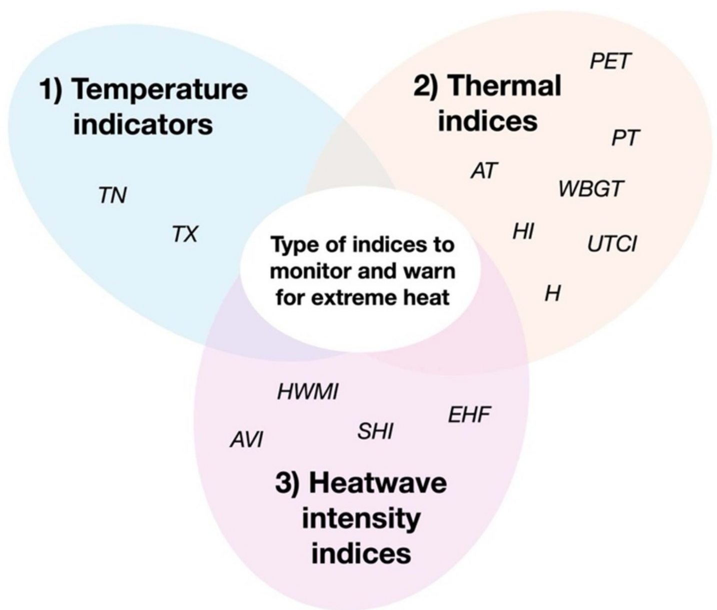

Figure 1. Typology for complementary extreme heat services and warnings. Indicators are grouped into three broad categories: (1) temperature-based indicators (e.g. TX = daily maximum temperature, TN = daily minimum temperature), (2) thermal stress indices (e.g. AT = apparent temperature, PET = physiologically equivalent temperature, PT = perceived temperature, WBGT = wet-bulb globe temperature, HI = heat index, H = humidex, UTCI = universal thermal climate index), and (3) heatwave intensity metrics (e.g. HWMI = heat wave magnitude index, AVI = heatwave average intensity, SHI = standardized heat index, EHF = excess heat factor). *Note: The indicators listed here are illustrative and not exhaustive within each category.*

are based on varying sets of assumptions that are not universally applicable across the population, require high-quality input data, and importantly, their forecasts are typically unreliable beyond a few days due to their dependency on multiple atmospheric parameters (trade-offs already highlighted in Section 2.2) (McGregor *et al* 2024). Their use is typically concentrated in specific sectors or regions, for example, the WBGT is used in public warning systems in Japan and Singapore, and for outdoor workers in Hong Kong.

Type 3: heatwave intensity indices: these indices are designed to reflect the cumulative and anomalous nature of heatwaves. Indices such as the excess heat factor (EHF) combine short- and long-term temperature baselines to identify sustained, locally significant cumulative heat (Nairn 2021). These indices quantify both the persistence (multi-day duration over days and nights) and magnitude (excess heat above climatological expectations) of heat, and in some cases, include acclimatization factors. Unlike Type 1 or Type 2 indices, which capture temperature anomalies or physiological stress on a given day (even when applied over multiple days), Type 3 indices measure the accumulated impact potential of heat over time. As such, they are well suited for impact-based forecasting, multi-hazard early warning systems, aligned with WMO's Severe Weather framework. Although still underused globally, these indices offer strong potential for standardizing environmental heatwave definitions and warning systems, including multi-hazard systems.

A harmonized typology helps ensure systems are fit for purpose. Most countries will benefit from developing complementary services across all three categories. Among them, heatwave intensity indices (Type 3) stand out as especially well aligned with impact-based and multi-hazard early warning systems, making them strong candidates to anchor national heatwave warnings. While temperature-based indicators (Type 1) remain valuable for climate monitoring, long-range services, and broad public communication (and continue to serve as the operational backbone of many systems due to their simplicity and high forecast skill), they represent a fundamentally different logic than intensity-based approaches. The latter offer a more risk-relevant way of capturing prolonged, anomalous heat, and are essential for advancing toward systems that reflect the cumulative nature of heat risk.

The goal is not to prescribe a single 'best' index, but to support informed choices by clarifying what each type captures, where it performs best, and the trade-offs involved. As countries expand or refine their systems, clearer guidance is needed to help meteorological services select indices that are scientifically robust and operationally feasible for national extreme heat services and warnings. For specific user groups or sectors, this may involve working collaboratively with meteorological services to co-develop tailored forecasts and products that support effective decision-making.

4.2. The role of transparency and convergence

As heat events increase in frequency and severity, meteorological services must be equipped to deliver tailored information across the full range of timescales, from climatologies and seasonal outlooks to multi-day warnings and real-time monitoring. While only a few advanced services currently operate across this full spectrum, expanding these capabilities is essential for more inclusive, responsive, and impact-based systems.

The harmonized typology presented offers a holistic model for convergence on a smaller set of standardized impact-based measures, central to consistent and effective extreme heat services. However, realizing the benefits of a harmonized typology in practice is not straightforward. Achieving this requires improved transparency and coordination. Many countries do not publish the criteria behind their warning systems, leaving researchers to reverse-engineer thresholds from media coverage (Chandra *et al* 2025). This limits comparability and prevents lower-capacity countries from learning from others. The Global Heat Health Information Network (GHHIN) is fostering a culture of transparency and exchange to accelerate capacity-building and scale up effective systems more rapidly, particularly in low- and middle-income countries (LMICs), where many systems are still in early stages of development. In practice, many LMICs still rely on basic T_{max} thresholds due to data limitations, even as demand for tailored, sector-relevant services continues to grow.

A tiered or phased approach to strengthening heat services is critical for scalability. Countries vary in data availability, institutional maturity, and technical capacity. Starting with what is feasible, while progressively expanding, allows systems to evolve without sacrificing relevance or scientific integrity.

Recognizing these gaps, WMO and WHO have called for more standardized, fit-for-purpose approaches. Their efforts, such as a working definition of heatwaves (WMO n.d.), updated guidance on heatwaves and heat-health warning system development, and a forthcoming handbook on extreme heat, reflect a growing push to improve the coherence, transparency, and impact-relevance of warning systems.

5. Conclusion

The current landscape of extreme heat services and warning systems is fragmented. Without greater clarity on the role and selection of indices, efforts to build effective, trusted, and scalable systems will continue to fall short.

As climate change accelerates the frequency, duration, and severity of extreme heat events, the need for coherent, risk-informed, and cross-sectoral warning systems becomes increasingly urgent. This Perspective proposes a typology to help clarify what different indices (temperature indicators, thermal indices, and heatwave intensity indices) capture, where they are generally suited for application, and how trade-offs can be managed.

Each type has distinct strengths: temperature indicators provide simplicity and high forecast skill; thermal stress indices reflect physiological burden and support sector-specific alerts especially in occupational or health contexts; and intensity-based indices offer strong potential for integration into impact-based and multi-hazard frameworks, as they capture the cumulative and anomalous nature of heat. Moving toward intensity-based approaches also reflects a conceptual shift, from treating heat as isolated threshold exceedances to understanding them as weather intensity meteorological phenomena with spatially detailed information.

Moving toward more consistent and transparent use of heat indices, grounded in clear typologies, robust evaluation, and local validation, can support global coordination, cross-border comparability, and progressive system development. Ultimately, clarifying the conceptual foundations of heat warning systems is a critical step toward protecting lives, informing early action, and reducing the rising human and societal toll of extreme heat in a rapidly warming world.

Data availability statement

No new data were created or analysed in this study.

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