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Iterative management of heat early warning systems in a changing climate

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Extreme heat is a leading weather-related cause of morbidity and mortality, with heat exposure becoming more widespread, frequent, and intense as climates change. The use of heat early warning and response systems (HEWSs) that integrate weather forecasts with risk assessment, communication, and reduction activities is increasingly widespread. HEWSs are frequently touted as an adaptation to climate change, but little attention has been paid to the question of how best to ensure effectiveness of HEWSs as climates change further. In this paper, we discuss findings showing that HEWSs satisfy the tenets of an intervention that facilitates adaptation, but climate change poses challenges infrequently addressed in heat action plans, particularly changes in the onset, duration, and intensity of dangerously warm temperatures, and changes over time in the relationships between temperature and health outcomes. Iterative management should be central to a HEWS, and iteration cycles should be of 5 years or less. Climate change adaptation and implementation science research frameworks can be used to identify HEWS modifications to improve their effectiveness as temperature continues to rise, incorporating scientific insights and new understanding of effective interventions. We conclude that, at a minimum, iterative management activities should involve planned reassessment at least every 5 years of hazard distribution, population-level vulnerability, and HEWS effectiveness.

Keywords: climate variability; climate change; heatwaves; adaptation; iterative management

Introduction

Extreme heat is a leading cause of weather-related mortality in the United States.[1] Exposure to high ambient temperature can lead to sharp increases in heat-related illness, as well as increases in heat-related morbidity and mortality associated with cardiorespiratory and other chronic health conditions.[2,3] These health impacts are potentially preventable; heat early warning and response systems (HEWSs)—a suite of activities linking weather forecasts with risk communication and reduction strategies[4]— are commonly employed to reduce population exposure and susceptibility to climate variability. Generally, HEWSs are built on the joint efforts of health systems and meteorological services to alert decision makers and the general public of impending, dangerously hot weather and to recommend strategies for avoiding heat exposure, minimizing progression of heat illness symptoms, and accessing care when needed.[3] Following the heatwave in Chicago, Illinois, in July 1995, HEWSs have proliferated to take advantage of increasing forecasting skill and understanding of the risks that extreme heat poses to human health.[3] On the basis of congruent evidence from several ecological studies, HEWSs appear to save lives[5–9] and likely reduce hospitalizations[8] related to extreme heat, although most HEWSs were not designed for rigorous evaluation; stronger evidence of efficacy is needed.[10] Improvements in the design and implementation of HEWSs could increase their effectiveness.[10]

A comprehensive HEWS has many components and its development and administration involves a host of administrative choices.[3] One of the first challenges is defining a period of dangerously hot weather. Heat is a complex hazard resulting from

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nyas13258 W3G-nyas.cls September 1, 2016 16:6

the interaction of solar radiation, atmospheric temperature, atmospheric moisture, soil moisture, the built environment, and wind speed or ventilation. Various approaches are used to determine the level of heat that is dangerous, including applying a statistical threshold to historical temperature records[11,12] and epidemiological analyses of associations between high temperatures and adverse health outcomes.[13] The goal of the analyses is to identify a threshold above which mortality (or another chosen health endpoint) increases during periods of extreme heat (e.g., an increase of several deaths per day or a specified change in mortality rate).

One of many considerations in defining a heatwave is that HEWSs are developed using historical observations. However, HEWSs operate on the basis of forecasts. Local meteorological services need to be able to forecast periods of high ambient temperature (and sometimes humidity) with reasonable skill several days in advance. Weather forecasting techniques have evolved rapidly owing to advanced satellite observations, ground observations, weather modeling, and data fusion techniques. The quality of weather forecasting affects estimated heat–mortality associations,[14] and the skill affects the robustness of forecasts several days in advance of a heatwave.[15]

Once the definition of a heatwave is determined, the HEWS administrators need to identify the location of particularly susceptible groups; pair warnings with an effective notification and response program; and specify evaluation criteria, such as acceptability, timeliness, and sensitivity and specificity.[3] Health communication strategies are also an important consideration, as HEWSs also typically include general public education and awareness, such as guidance on actions to reduce personal health risks, and sometimes targeted risk communication and other activities aimed at high-risk populations.

Climate change presents a number of challenges to HEWSs, from shifts in heat hazard onset, frequency, intensity, and distribution, to ongoing changes in population susceptibility. Little attention has been paid to these challenges and how they might be approached. Below, we discuss the challenges that climate change poses to HEWSs, strategies for modifying HEWSs so they remain adaptive to climate change, and highlight the importance of building a strong evidence base related to these changes in order to facilitate climate change adaptation activities in public health.

Current HEWSs may not be adaptive to climate change

It is generally assumed that, because HEWSs reduce susceptibility to climate variability, these systems will also increase resilience to a changing climate, and the presence or absence of a HEWS in a given location has been proposed as an indicator of climate change adaptation in its health sector.[16] HEWSs are frequently highlighted as part of a ministry or department of health's portfolio of adaptation options to manage the health risks of climate change, such as the ongoing efforts in many countries in Europe to implement HEWSs. HEWSs satisfy the tenets of climate change adaptation by reducing the current adaptation deficit to climate variability; being mainstreamed within local and national policies and programs; having low regrets as the climate continues to change; aligning adaptation with sustainable development goals; and being cost-effective, efficient, and equitable. By these criteria, HEWSs are an important adaptation measure. HEWSs are definitely low-regret strategies, with extreme heat events projected to increase in frequency, intensity, and duration regardless of the magnitude of climate change.[17] Further, HEWSs are cost-effective, saving lives with rather limited investments.[18]

However, HEWSs may not promote adaptation to the extent expected if there is no explicit iterative management plan to update thresholds and activities in response to changes in temperature and population risk profiles. By focusing on historical patterns and scientific understanding of the health impacts, there is the potential for false security in the face of a shifting hazard if there is no explicit provision for updating HEWS activities to prepare for further changes in the climate. Further evidence is needed of the effectiveness not just of HEWSs overall, but also of specific interventions to ensure actions are cost-effective, targeted to the most vulnerable populations, and as adaptive as possible in a changing climate.

Challenges to HEWSs from a changing climate

As climate change accelerates, HEWSs will need to evolve in order to ensure continued efficacy.

The most important challenges in adaptive management of HEWSs relate to the need for updated temperature–health outcome thresholds; for system calibration, and for targeted risk communication as the hazard distribution shifts, population risk profiles change, and greater scientific knowledge is gained about the health impacts. Other challenges relate to the need for new interventions to manage risks as hazard severity increases, more people are exposed, and available prevention measures may be overwhelmed. Additional information will be needed on risk characterization and communication, changing profiles of exposure to extreme heat, changing susceptibility that will affect response plans, and changing communications about extreme heat events and appropriate public health responses.

A more nuanced understanding and communication of heat–health risks is needed; extreme heat events are dissimilar to other extreme weather and climate events in that the exposure and associated population health impacts are generally best described as continuous functions, not thresholds (e.g., when a period of dry weather becomes a drought) or step functions (e.g., a flood or tornado), regardless of how they are treated in the course of programmatic decisions. In addition, specific health outcomes are associated with different points on the exposure curve.[19] It is therefore challenging to decide when hot weather becomes dangerous to the population as a whole and when additional protective interventions are needed. Moreover, the answers to those questions vary by population groups and particular subsets, such as older adults, who experience heightened susceptibility before others. These population-specific risk dynamics can complicate HEWS administration further, depending on whether the system is focused on the population as a whole or on particular vulnerable populations.

Generally, for practical purposes, a single threshold is chosen for a given location and the general population, typically based on recent historical temperature–mortality relationships, and, then, this threshold is adjusted based on perceptions of risk tolerance and how many times a warning could be called for extreme heat events.[3] Thresholds for response will likely need to be changed with population acclimatization to increases in the frequency, intensity, and duration of periods of extreme heat.[20] The question of how best to minimize "alert fatigue" may need to be revisited as susceptibilities shift with climate change. Overall, processes for evaluating these considerations may need to be included in HEWSs.[20]

Modifying HEWSs to be adaptive to climate change

The components of HEWSs and the processes for reviewing them will need to be adjusted, as exposure and vulnerability shift with climate change.

Time period covered by HEWSs

An increased understanding is needed of whether seasonal risk patterns will change with increasing temperatures and extreme events, and how HEWSs can best prepare for these shifts, to ensure populations continue to be prepared when dangerous weather patterns occur. In the Northern Hemisphere, most HEWSs are initiated around mid- to late-May and are turned off around mid- to late-September.[21] However, Spring is arriving sooner and Fall starting later,[17] extending the period during which extreme heat events can occur. Missing early-season heatwaves is particularly concerning because events early in the summer may be more deadly when the population has not yet physiologically acclimatized to warmer temperatures.[22] Ending a HEWS in mid-September may miss extreme heat events later in the Fall, leaving the population without adequate warning for temperatures that could lead to higher morbidity and mortality. These trends will continue in a changing climate, raising the question of when to adjust the time period covered by a HEWS.

Further, the health impacts of extreme heat exposures are generally higher where high ambient temperatures are less common;[23] therefore, over time, cities and regions will eventually transition to having populations with greater acclimatization to extreme heat and, thus, with lower mortality during such events, assuming future events are of similar intensity and duration to those of today. Monitoring and evaluation are needed to understand when and to what extent such a transition takes place, with attendant implications for an effective HEWS. This also suggests that HEWSs should consider recent temperature patterns when planning a response for a particular year.

The health and meteorological departments involved in operating the system should regularly revisit operational decisions, taking into consideration recent and projected trends in extreme heat events, in order to decide when to make adjustments and how to communicate adjustments to stakeholders and the public.

Duration and return periods of extreme heat events

The duration of extreme heat events is projected to lengthen and the return period between heatwaves is projected to shorten with climate change,[17] raising questions of how to modify current, and design new, HEWSs to take these changes into account. Heat-related mortality is positively associated with heatwave duration;[11] therefore, prolonged heatwaves may require responses in addition to activities contained in typical HEWSs. Well-designed systems include criteria for declaring and ending a heat warning.[24] However, identifying the end of an extreme heat event may be less clear as continued warming leads to extended periods of high ambient temperature, with temperatures moving above and below thresholds for declaring heat warnings.

Geographic extent

Continuing emissions of greenhouse gas are increasing the frequency, duration, and extent of extreme heat events.[17] The geographic extent of extreme heat events also appears to be increasing,[25] consistent with the additional energy being added to the atmosphere by rising concentrations of greenhouse gases. Most HEWSs have been developed and deployed on a municipal level because of the importance of the local context. Continuing to scope HEWSs at a local level raises the question of how to coordinate HEWSs most effectively across larger geographical areas in order to ensure coherence of warnings and suggested actions, while maintaining important local variations in planning and response. Research is needed to determine whether the same warnings should be provided across the urban–rural gradient or whether land-use and other differences affecting heat intensity and population susceptibility should be taken into account. Coordination of heat warnings across larger spaces could facilitate risk communication and standardize messaging to susceptible populations and regions outside main cities, but it would be best to do so within a structure through which local communities can add information important to their context, as is done today in the United States when snow warnings come with information on closures of specific businesses and schools.

A related and critical consideration is that thresholds for declaring heat warnings vary by location. The temperature at which morbidity and mortality significantly increase varies geographically.[23] Therefore, different regions would be expected to declare heat warnings at different ambient temperatures.[26] To become adaptive to a changing climate, these HEWSs should consider promoting interoperability of operations, including how to maintain different thresholds that reflect local vulnerabilities, while at the same time, ensuring consistent and clear communications about thresholds in each location. As weather and related information is increasingly obtained through social media and less frequently from broadcast meteorologists, coordinating messaging would reduce potential confusion from multiple, and perhaps inconsistent, communications at the time that a heat warning is declared (and ended).

Including new information in response plans

To remain effective in a changing climate, heat response plans need to incorporate new scientific information on particularly susceptible groups and on the health impacts (morbidity and mortality) associated with high temperatures. There is a rich and growing scientific literature on extreme heat vulnerability, with often slow uptake into HEWSs. Below are examples of some research findings that could be incorporated into HEWSs.

- In some regions, mortality increases with the length of an extreme heat event.[27,28] If this is the case for the region covered by a HEWS, then as climate change increases heatwave length, HEWS administrators will need to consider how to communicate risks over longer time periods to motivate effective actions. The widespread assumption of acclimatization means that people are unlikely to think that they remain at risk, even when that is, in fact, the case. Further, there are challenges when communication relies on broadcast meteorologists; a heatwave is no longer "news" when it lasts for an extended period.
- Decreasing mortality during the winter season may result in a larger pool of individuals the following summer with higher susceptibility to extreme heat events.[29–31] If mortality during the winter season does decline with climate

change, then HEWSs will need to consider what the changing mortality patterns could mean for susceptible populations and how best to manage these patterns, taking into consideration other factors affecting susceptibility to extreme heat.

- Associations between temperature and particular health outcomes,[32] such as those between temperature and mortality, vary by location. As information regarding these associations accumulates, HEWS administrators and local health officials will need to determine how HEWSs should be structured to prevent specific adverse outcomes and develop surveillance activities to monitor important information. This could involve differential impacts based on stratified analysis of population susceptibility to identify impacts with the largest overall burden of disease.[32,33]
- Projections of the health risks of extreme heat events generally assume consistent exposure–response relationships going forward.[34] However, declining mortality during hot weather in some regions[35,36] suggests exposure–response relationships will change over time. HEWSs should regularly review the state of knowledge, analyze local data on exposure–response relationships, and determine other changes in the size of susceptible populations (e.g., number of older adults), to revisit whether thresholds may need to be adjusted for the system to maintain effectiveness and to determine when additional efforts are needed when temperatures significantly exceed historic experience, such as the European extreme heat event in 2003.[37]
- With heatwaves increasing in intensity, the distribution of ambient temperatures will have increasingly fat tails.[38] Yet, few studies on the health risks of high temperatures focus on estimating exposure–response relationships within the tails of the distribution.[34] There is some evidence in some locations that these relationships may be nonlinear, implying that higher temperatures may increase morbidity and mortality by more than what is projected.[34]
- Reasons proposed for the declining overall mortality associated with extreme heat include increased access to air conditioning and cooling centers.[35,36] With penetration of air conditioning in the United States reaching saturation (two-thirds of all homes have air conditioners; http://energy.gov/energysaver/air-conditioning), the slope of the downward heat-related mortality trend may slow over time. Monitoring heat-related mortality would provide insights into shifting mortality patterns, preferably designed to take into consideration the extent to which various components of HEWSs reduce mortality.

Communication plans

Although HEWSs are known to save lives,[5,9,18] it is not yet possible to identify which components of such systems are the most important contributors, because systems were not designed to facilitate that understanding and there has been no systematic investigation of which HEWS components are the most effective. With new systems being developed worldwide, there is an opportunity to design trials to understand which components are critical for reducing morbidity and mortality, which would then increase the effectiveness of communication plans.

With advances in mapping regions within cities with higher temperatures during heatwaves and locations with higher numbers of susceptible people,[39–42] there is an opportunity to move beyond general statements by broadcast meteorologists to take advantage of social media and other communications to provide more personalized warnings. For example, census population data with information on socioeconomic status, age, population density, building age, and land-surface temperature were combined to create a heat and health risk index to tailor extreme heat event adaptation plans in Rennes, France.[39] Such information can be used to identify individuals at particular risk and to find ways to provide them personal messages. For example, individuals taking certain drugs that inhibit sweating (e.g., beta-blockers, some mental wellness drugs) are at higher risk during an extreme heat event. Healthcare providers and pharmacists could be provided with information to be communicated to these individuals, ensuring that individuals are aware of the risks and the options for protecting themselves during heatwaves. A particular challenge is the low awareness that heat is a health risk.[43–45]

Increasing understanding of high-risk areas can also be used for resource planning by healthcare

Table 1. **Major challenges to HEWSs from a changing climate, related HEWS management decisions, appropriate time frames for review, and suggested level for efficient information management**

Challenge in a changing climate	Example of HEWS management decisions	Relevant review time frame	Suggested level for information management
Time period covered by HEWSs	When to activate and discontinue forecasting and warning activities; whether thresholds should be lower for the first half of a heat season	Annually, with intensive 5-year review	Local to regional (e.g., state)
Duration and return periods of extreme heat events	Whether additional protections should be triggered by events of a certain duration and/or number of events in a season	Annually, with intensive 5-year review	Regional to national
Geographic extent	Primary coverage area for HEWS	Every 5 years	Regional
Changes in susceptibility associated with winter severity	Whether to adjust preparedness activities in anticipation of larger mortality displacement events	Every 5 years	Regional to national
Changing priority health outcomes on a population basis	What exposure–outcome associations to prioritize in developing warnings	Every 5 years	Local to regional
Changing exposure–outcome associations	Whether and how to adjust warnings based on increasing (or decreasing) risk	Every 5–10 years	Regional to national
Novel information regarding exposure–outcome associations at far extremes	Whether to adjust preparedness activities for far extremes	Every 5 years	Regional to national
Novel information regarding intervention efficacy	What interventions to include and prioritize	Every 5 years	National to international

providers. Heatwaves in many regions increase emergency room visits;[46] therefore, increasing skill in forecasting heatwaves can be used to identify human resource needs, in order to increase preparedness to meet demands for services during an extreme heat event.

Another possibility is to consider changing the timing of warnings about heatwave-related health risks from a limited number of risk levels directed to the entire population to more nuanced warnings that take particularly susceptible groups into consideration. With increasing skill in forecasting heatwaves, particularly subseasonal forecasts, HEWSs could use this additional time and greater information on who is most at risk to establish a series of thresholds based on susceptibility. For example, a few days before the forecast start of an extreme heat event, there could be warnings for adults over the age of 65 years, parents of infants and children, individuals taking certain medications, and individuals with certain chronic diseases such as diabetes, that temperatures are on the increase and they might consider taking preventive actions before an extreme event is declared. This could raise awareness in highly susceptible groups and in those caring for them of appropriate behavioral changes to

Table 2. Climate change adaptation research domains, relationship with adaptation activities in the health sector, and corresponding domains in implementation science

Climate change adaptation research domain	General focus in health adaptation activities	Implementation science research domain
Purposefulness of assessment	Planned activities to support essential public health services,[28] including clinical care provision	Outer settings (e.g., risk perception, political context) and inner settings (e.g., institutional planning horizons)
Timing of adaptation	Recent past, present, and near future (i.e., present ± two decades), in response to perceived threats and threats anticipated in short- to medium-term	Intervention characteristics, implementation processes
Temporal and spatial scope of adaptation activity	Temporal: present to near future Spatial: local to national	Intervention characteristics, implementation processes
Adaptation function and effects	Activities in 10 essential public health services	Intervention characteristics, implementation processes, characteristics of individuals pursuing interventions
Adaptation form	Policies, programs, funding priorities, infrastructure planning	Intervention characteristics, implementation processes
Adaptation performance	Avoided health impacts, cost-effectiveness, equity	Outer settings, implementation processes

reduce risks. Over the next few days, the warnings could include more population groups. Increasing frequency of extreme heat events would need to be taken into consideration so that warning fatigue does not set in.

Iterative management activities

Ensuring that HEWSs are responsive to changing hazard distributions and population risk profiles will require regular reassessment of HEWS activities. To some extent, this is likely to be a routine part of annual or semiannual evaluation efforts. Nevertheless, explicit and regular attention to the challenges presented above will increase the likelihood that HEWSs remain adaptive to a changing climate. Table 1 outlines climate change–related challenges, the minimum timeframe for reviewing HEWS activities in each domain, and provides suggestions as to the level at which information should be collected and disseminated to facilitate timely decision making.

Implementation science, climate change adaptation, and HEWSs

An evidence-based approach to climate change adaptation in public health includes attention not just to the evidence of impacts, but also to the evidence related to the timing and effectiveness of implementation.[47] Implementation science is an emerging discipline in health (both population health and clinical care) that focuses on knowledge translation in practice across various settings and includes assessment of policy impacts. This emerging field has established research frameworks,[48] the primary research domains of which relate to intervention characteristics, outer settings (social, political, and economic contexts[49]), inner settings (structural and cultural contexts[49]), characteristics of individuals implementing interventions, and implementation processes.[48] Implementation science is recognized by major research funders as central to the process of knowledge translation[50] and has received substantial research funding in recent years,[51] but has yet to be applied to climate change.

The science of climate change adaptation developed separately, with its own research frameworks[52] and substantial growth in research activities across a wide range of sectors.[53] Proposed domains for climate change adaptation science include purposefulness of the research or assessment (intended application), timing of the adaptation (in reference to emergence of climatic stressors), temporal and

nyas13258 W3G-nyas.cls September 1, 2016 16:6

spatial scope of the activity, adaptation function and effects (the functional nature of the adaptation effort, for example, infrastructure protection), adaptation form (vehicle(s) used, for example, policy), and adaptation performance (e.g., cost effectiveness, equity).[52] A subset of this work focuses on adaptation in the health sector.[54–56]

Given the health sector's growing familiarity with, and investment in, implementation science and its increasing climate change adaptation needs, it is likely that the two disciplines will converge in the coming years. The climate change adaptation science research agenda is overall larger in scope than the health implementation science research agenda. As outlined in Table 2, it is relatively straightforward to map climate change adaptation research domains to health sector adaptation activities and to corresponding domains in implementation science research. Greater integration of adaptation and implementation science has the potential to strengthen both approaches in order to ensure that population health is protected and advanced.

Conclusion

Incorporating climate change into HEWSs means explicitly taking an iterative risk management approach. This requires acknowledging that current systems will need to be regularly evaluated and updated to ensure continued effectiveness, taking into consideration recent and projected changes in climate and updated scientific understanding of particularly susceptible population groups. Below are types of questions that should be asked regularly during evaluations.

- When should the system be adjusted to take into account changing heat season onset, length, and intensity?
- How and when should thresholds for warnings be re-evaluated, and should thresholds focus on the population in general or specific vulnerable subsets?
- How should systems incorporate actions for when temperature extremes significantly exceed recent experience and regularly incorporate new data on associations between temperature and population health risk?
- How should population acclimatization be monitored and changes in thresholds and response plans be incorporated?
- What spatial scale is most appropriate for HEWS, and should HEWS activities from different adjacent locales be either coordinated or integrated?
- Which changes in other drivers, such as behavioral patterns, awareness of risks, changes in the built environment, and infrastructure changes, among others, should be monitored and how often?
- How should emerging research be tracked and findings integrated into HEWS activities?

The answers to these questions will to some extent depend on the local context, with the choices made discussed and coordinated with neighboring HEWSs to ensure consistency, so that extreme heat-related morbidity and mortality continue to decline even as exposure and vulnerability increase over the coming decades.

It will be important for the health community to continue to make an effort to document HEWS activities and programmatic successes and challenges and to evaluate specific components of HEWS activities. A robust body of climate change adaptation and implementation science can be built around HEWS. There are abundant opportunities to add to the evidence base, given the diverse settings in which HEWSs are operating globally, the widely varying population susceptibility in those settings, and the large variability in heat hazards that those HEWSs help protect against. This evidence will be crucial to facilitating HEWS adaptive management in the face of ongoing climate change and as a roadmap to developing other climate change adaptation activities in the health sector.

Conflicts of interest

The authors declare no conflicts of interest.

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