A Stitch in Time: Improving Public Health Early Warning Systems for Extreme Weather Events

Kristie L. Ebi and Jordana K. Schmier

From Exponent, Inc., Alexandria, VA.

Received for publication July 30, 2004; accepted for publication January 18, 2005.

INTRODUCTION

Extreme weather events, particularly floods and heat waves, annually affect millions of people and cause billions of dollars of damage. In 2003, in Europe, Canada, and the United States, floods and storms caused 15 deaths and US$2.97 billion in total damages, and the extended heat wave in Europe caused more than 20,000 excess deaths (1); the impacts in developing countries were substantially larger. There is a growing body of scientific research suggesting that the frequency and intensity of extreme weather events are likely to increase over the coming decades as a consequence of global climate change (2). These events cannot be prevented, but their consequences can be reduced by taking advantage of advances in meteorologic forecasting in the development and implementation of early warning systems that target vulnerable regions and populations.

The skill with which weather and climatic events can be forecast has increased significantly over the past 30 years as more has been learned about the climate system. During this period, weather forecasting improved from the same-day forecast to the advance forecast. Our understanding of the mechanics and teleconnections of El Niño/Southern Oscillation now provides us with the capacity for seasonal and annual forecasting—assumed as recently as the 1970s to be more science fiction than fact (3). In fact, Chen et al. (4) recently suggested that El Niño events can be predicted 2 years in advance. Public health professionals have the opportunity to integrate weather- and climate-related information into local and regional risk management plans to reduce the detrimental health effects of hazards as diverse as tropical cyclones, floods, heat waves, wildfires, and droughts (5, 6).

TRENDS IN EXTREME WEATHER EVENTS

Scientists began to keep instrumental records of temperature, precipitation, and other weather elements in the 1860s. In its Third Assessment Report, the Intergovernmental Panel on Climate Change evaluated this record and concluded that there was an increase in the frequency of extreme high monthly and seasonal average temperatures over the 20th century (5). The Intergovernmental Panel on Climate Change also concluded that precipitation increased by 0.5–1.0 percent per decade over most mid and high latitudes of the Northern Hemisphere continents, with a 2–4 percent increase in the frequency of heavy precipitation events at those latitudes during the latter half of the 20th century (7). In addition, it is very likely that El Niño events have been more frequent, persistent, and intense since the mid-1970s, in comparison with the previous 100 years. These trends are a consequence of a warming climate, particularly over the mid and high latitudes of continents in the Northern Hemisphere. Northern Hemisphere temperatures in the 1990s were higher than at any other time in the past 6–10 centuries (7). The warmth of the 1990s was outside the 95 percent confidence interval of temperature uncertainty, defined by historical variation, during even the warmest periods of the last millennium (8). The increase in temperature over the 20th century was likely to have been the largest of any century during the past millennium. The projections for the 21st century are for more, and more rapid, change in temperature and precipitation than was experienced during the last century (8).

Interactions between changes in the mean and variability of weather variables complicate projections of possible future trends in extreme events (9). Assuming a normal distribution of surface temperatures, one can envision three scenarios of increasing temperature (10). In the first scenario, there is a simple shift in mean temperature without a change in the variance (e.g., the shape of the curve would remain the same). If that occurred, there would be a decrease in cold weather and an increase in both hot weather and record hot weather. The second scenario is an increase in the variance without a change in mean temperature; this would result in an increased frequency of cold and hot weather, with a decreasing frequency of weather that could be considered average under the previous climate (i.e., the shape of the
curve would become flatter). Finally, if there were a shift in both the mean and the variance, there would be a small decrease in cold weather and a significant increase in both hot weather and record hot weather. The patterns for precipitation might differ, because precipitation is not well approximated by a normal distribution; there could be changes such as a shift in frequency or a shift in distribution, either of which could affect overall intensity. Because changes in the frequency of many extremes can be surprisingly large for seemingly modest changes in mean climate, there is growing concern that future weather patterns will resemble the third scenario and that what is currently considered an extreme event may become common (11).

Easterling et al. (2) summarized results from the modeling of different types of climate extremes for the 21st century. For simple extremes based on climate statistics, the authors concluded that the following changes are very likely (90–99 percent probability) to occur by the end of the 21st century: higher maximum temperatures; more hot summer days; an increase in the heat index; more 1-day heavy precipitation events; and more multiday heavy precipitation events. In terms of complex event-driven climate extremes, it is very likely that there will be more heat waves, and it is possible (33–66 percent probability) to occur by the end of the 21st century:

- More intense mid-latitude storms and more intense El Niño events.
- More intense hurricanes and typhoons globally.
- More intense heat waves and droughts in low-latitude regions, where evapotranspiration is high.
- More intense cold waves in high-latitude regions.
- More intense hurricanes and typhoons in the Atlantic and the East Pacific.
- More intense heat waves and droughts in about half of all mid-latitude regions.
- A likely consequence of increased climate variability will be surprises with regard to the timing, intensity, location, and duration of extreme weather events (12). This means that all mid-latitude regions need to be prepared for extreme weather events, regardless of whether they have occurred over the past century. Unfortunately, scientists and policymakers have been focusing more on the uncertainty about the rate and intensity of changes in climate variability than on the certainty that without adequate preparation, more extreme events will lead to increased morbidity and mortality. Flooding and heat waves are of particular concern because of recent increases in mortality (13).

Effective prediction and prevention programs that incorporate advances in climate forecasting can be designed and implemented with a better understanding of the subpopulations at risk and of the information needed for effective response to warnings (5, 6). The value of these early warning systems will increase as the projections of increased climate variability are realized. Extreme weather events cannot be prevented, but population vulnerability to these events can be reduced.

THE PUBLIC HEALTH IMPACTS OF EXTREME WEATHER EVENTS

Table 1 summarizes the health impacts of heat waves, extreme rainfall, floods, and droughts. Some of the health outcomes associated with extreme weather events have well-described etiologies; for example, there have been numerous studies of the association between heat waves and mortality and morbidity, and of the increased frequency of disease outbreaks following floods (14–16). Mortality and morbidity immediately and directly associated with an extreme event are often documented, but other health outcomes, such as the mental health effects associated with floods, are less well studied (14). More consistent and comprehensive data collection during and after extreme weather events will lead to a better understanding of the morbidity and mortality associated with such events.

### NEED FOR AND LIMITATIONS OF PUBLIC HEALTH SURVEILLANCE

Surveillance during the time period immediately surrounding an extreme weather event is a key public health activity. Public health professionals must determine whether the event is associated with an increase in disease (such as diarrheal disease after a flood) so that appropriate measures (such as a “boil water” alert) can be instituted. In addition, surveillance of age- and cause-specific deaths over time is needed for calculation of baseline or normal mortality rates in order to recognize increases in mortality over what would have been expected (17). However, because there can be a considerable time lag between when deaths occur and when data become available for analysis by public health authorities, surveillance during an extreme event is insufficient for determining when to implement public health interventions.

The limitations of existing surveillance were demonstrated during the 2003 European heat wave. This heat wave, which caused approximately 15,000 excess deaths in France during a 2-week period, took French public authorities by surprise (18). There are numerous reasons why timely responses to this event were not implemented, among them the fact that surveillance systems were not adequately designed to detect and respond to a heat wave. Surveillance

---

### TABLE 1. Summary of the health impacts of extreme weather events*

<table>
<thead>
<tr>
<th>Extreme weather event</th>
<th>Health impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat wave</td>
<td>Short-term increases in cardiovascular respiratory mortality</td>
</tr>
<tr>
<td></td>
<td>Increases in deaths from heat stroke</td>
</tr>
<tr>
<td>Extreme rainfall</td>
<td>Transportation of waterborne disease-causing organisms into the water supply</td>
</tr>
<tr>
<td>Flood</td>
<td>Deaths and injuries</td>
</tr>
<tr>
<td></td>
<td>Disruption of the water supply and sanitation systems</td>
</tr>
<tr>
<td></td>
<td>Possible damage to transportation systems and the health care infrastructure</td>
</tr>
<tr>
<td></td>
<td>Provision of breeding sites for mosquito vectors, with resulting outbreaks of disease</td>
</tr>
<tr>
<td></td>
<td>Post-traumatic stress disorder</td>
</tr>
<tr>
<td>Drought</td>
<td>Reduction in availability of water for hygiene, which can lead to diarrheal and respiratory diseases</td>
</tr>
<tr>
<td></td>
<td>Reduction in food availability in populations dependent on household agriculture, which can lead to malnutrition and starvation</td>
</tr>
</tbody>
</table>

* Sources: Hajat et al. (14), Kovats et al. (15), Malilay (16), and Kilbourne (37).
systems did not provide authorities with information quickly enough to detect the increased number of deaths in time to implement interventions. A retrospective assessment found that there had been approximately 3,900 deaths at the time when only 10 deaths had been reported (18). Surveillance systems were not designed to recognize increases in morbidity and mortality among persons with chronic diseases, such as cardiovascular and respiratory conditions. In addition, even if surveillance systems had been adequate to detect an increase in morbidity, existing emergency public health interventions were not designed to address sudden increases in endemic and common diseases. Another problem was the large numbers of people at risk; it was estimated that there were 6 million people at risk during the heat wave, of which 1 million were at very high risk.

There were few widely available and efficient measures in France for reducing heat-related mortality, especially with so many people at risk. Air conditioning may have saved lives but was generally not available, particularly for the populations at highest risk, such as elderly persons in nursing homes. France is now developing a heat health warning system and a response plan, which have been shown in other cities to reduce mortality from extreme heat (19).

**EARLY WARNING SYSTEMS TO REDUCE MORBIDITY AND MORTALITY**

Improvements in surveillance systems can only partly address the health impacts of extreme weather events because, even if timely, recognition of an increase in adverse health outcomes does not always translate into practical and effective responses; all warnings are predictions, but not all predictions are warnings. Public health professionals need to increase their focus on prediction and prevention in order to mitigate the health consequences of extreme events. The addition of early warning systems to existing surveillance mechanisms, coupled with effective response capabilities, can both reduce current vulnerability and increase resilience to future extreme events (20).

For example, early warnings of flooding risk have been shown to be effective in reducing flood-related deaths when the warning is coupled with appropriate responses by citizens and emergency responders (16). An example is the difference between the 1993–1994 flooding along the Rhine and Meuse rivers in Germany and the 1995 flooding along those same rivers (21). Persistent high precipitation caused both events. The two floods had similar characteristics, although the 1993–1994 flood had a second peak discharge. Ten people lost their lives in the 1993–1994 flood, and the total damage in Belgium, Germany, France, and the Netherlands was estimated at US$900 million (21–23). The economic cost of the 1995 flood in Germany was reduced by about half, presumably because people were aware of the risks and made appropriate behavioral and other changes.

Surprisingly few heat wave early warning systems have been implemented, given the evidence that they can reduce mortality (19, 24). For example, the Philadelphia Hot Weather-Health Watch/Warning System was initiated in 1995 to alert the population to take a variety of precautionary actions during a heat wave (24). In an evaluation of the system, it was estimated that issuing a warning saved, on average, 2.6 lives for each warning day and for 3 days after the warning ended; the system saved an estimated 117 lives over a 3-year period. However, at the time of the 2003 European heat wave, only two cities in the World Health Organization European region—Rome, Italy, and Lisbon, Portugal—had operational heat health warning systems (25–27). In the United States, a recent review of 18 cities vulnerable to heat waves found that 10 had written response plans, with one third of the plans being no more than cursory (28).

For flooding, which is the most common natural disaster in Europe, the emphasis in disaster management has been on postdisaster improvisation rather than predisaster planning (14). There is a need for more good-quality epidemiologic data before vulnerability indices can be used operationally to minimize the health effects of flooding. The studies that have been conducted have primarily focused on assessing larger events, although more frequent smaller events may result in a greater health burden. Furthermore, different types of floods may require different types of intervention strategies.

**COMPONENTS OF A PUBLIC HEALTH EARLY WARNING SYSTEM**

Whereas surveillance systems are intended to detect disease outbreaks and measure and summarize data on such outbreaks as they occur, early warning systems for extreme weather and climatic events are designed to alert the population and relevant authorities in advance about developing adverse meteorologic conditions and then to implement effective measures to reduce adverse health outcomes during and after the event. A basic requirement for an early warning system is that the community or region have an adequate public health and social infrastructure, including the political will, to undertake the design and implementation of such a system. The principal components of an early warning system include identification and forecasting of the event, prediction of the possible health outcomes, an effective and timely response plan, and an ongoing evaluation of the system and its components. The system should be developed in collaboration with all relevant stakeholders to ensure that the issues of greatest concern are identified and addressed, thus increasing the likelihood of success. Stakeholders include the agencies and/or organizations that will fund the development and operation of the system, the groups that will be expected to take action, and those likely to be affected by an extreme event. Inclusion of persons previously affected by extreme events may provide local knowledge about responses and their effectiveness.

**Meteorologic identification and forecasting of extreme events**

What constitutes an extreme event needs to be defined in collaboration with relevant agencies and stakeholders, taking into consideration the factors that determine risk in
a particular population. Risk can be viewed as a combination of
the probability that an adverse event will occur and the
consequences of that event (29). Public health responses
should consider both, because the interventions developed
for high-probability events with minor consequences (e.g.,
a heavy rain event not associated with flooding) will differ
from the responses for low-probability events with major
consequences (e.g., the 2003 European heat wave). A
variety of population-specific factors determine whether
an extreme event poses a risk, including cultural factors,
economic factors, the status of the public health infrastruc-
ture, etc. For example, what is considered a “hot” day varies
considerably by latitude and across the summer season,
requiring local determination of risk.

Public health authorities must collaborate with meteo-
rologic organizations to understand the accuracy and timing
of warnings, in order to develop mechanisms for coordination
during an extreme event. Particularly for rapidly developing
events, such as heat waves and floods, public health
agencies need to understand what information will be
available so that the effectiveness of interventions can be
maximized. For example, some heat wave early warning
systems provide initial warnings 48 hours in advance (30).
Various activities are implemented as forecasts are further
refined.

Climate change projections suggest that past weather is
no longer a prologue for the future; therefore, early warning
systems and other public health interventions need to
incorporate plans for an unpredictable future. The develop-
ment of an early warning system should include the creation
of scenarios for plausible future weather anomalies to
ensure that the system can accommodate the increasing
frequency and severity of extreme events. For example, the
weather anomaly that resulted in the 2003 European heat
wave was much larger than anomalies considered in the
development of the heat health warning systems imple-
mented in Rome and Lisbon (L. S. Kalkstein, University of
Delaware, personal communication, 2004). This event may
be a harbinger of future European summers and provides
a warning to other regions (31). In addition, it would be
useful to develop scenarios incorporating multiple events
with impacts that extend beyond the traditional health
impacts. For example, if a heat wave resulted in the
shutdown of power plants that supplied electricity to a region
and alternative sources of power were not available,
responses would need to be developed for a range of health
impacts and other impacts. Similarly, extreme heat accom-
panying a drought (as in Europe in 2003) might adversely
affect agriculture or damage infrastructure such as rail lines,
resulting in derailments and transportation problems.

Prediction of possible health outcomes

Knowing that an extreme event has been forecast is
insufficient information for the design of a response plan.
There needs to be a model that can use the meteorologic
forecast, along with known associations between weather
conditions and health outcomes, to predict possible health
burdens in vulnerable populations. The output of the model
should be indicators of disease incidence that can be reliably
and quickly measured so that effective responses can be
implemented. The model must be accurate, population- and
location-specific, timely, and flexible (32). Disease pre-
diction models should consider not just weather but also
confounding or modifying factors that could affect the
potential for an outbreak. For example, heat waves may be
associated with high concentrations of air pollutants, so
models should evaluate their separate and joint effects.

The developers of such models must describe model
uncertainties and assumptions explicitly. All models have
multiple sources of uncertainty, from data uncertainties to
incomplete understanding of disease etiology. The sensitiv-
ity and specificity of a predictive model have implications for
the design of interventions. False-positives (issuing a warn-
ing when none was required) and false-negatives (not issuing
a warning when one was needed) have consequences, not
only in terms of morbidity and mortality but also in terms of
public willingness to rely on subsequent warnings. Incorpo-
rating an understanding of these uncertainties and their
associated costs into the design of an early warning system
could improve its effectiveness.

Response plan

Accurate predictions of impending extreme events and
their health impacts alone are not sufficient for developing an
early warning system; an effective response plan is essential
for reducing the predicted burden of disease (32). The
design and implementation of response activities should be
carried out in a transparent manner that includes all stake-
holders in the process and should reflect the cultural, social,
economic, and political context and constraints of the
targeted region (12). The characteristics of an early warning
response plan are informed by the political, social, and
cultural setting in which the system operates, as well as the
specifics of the event (12). The appropriateness of the plan’s
components, including thresholds of action and the inter-
ventions enacted, must be evaluated and modified to
maximize response effectiveness for the relevant community
or region. For example, some heat wave early warning
systems in the United States have two levels of health alerts:
a “watch,” which indicates that meteorologic conditions are
such that a heat wave could arise, and a “warning,” which
indicates that a heat wave has started (30). The American
public understands the terms “watch” and “warning”
because they have been used by the National Weather
Service in early warning systems for other climatic events,
such as tornados. This is not true in other regions. The United
Kingdom heat wave plan has four levels of response:
“awareness,” “alert,” “heat wave,” and “emergency” (33).

A response plan for extreme weather events should
incorporate components for both implementation and eval-
uation of effectiveness. The implementation component
should, at a minimum, include modules addressing 1) where
the response plan will be implemented; 2) when interven-
tions will be implemented, including thresholds for action;
3) what interventions will be implemented; 4) how the
response plan will be implemented; and 5) to whom the
interventions will be communicated.
Where the response plan will be implemented. The responsible agencies and institutions need to agree on geographic boundaries for the response plan. This is particularly an issue when a potential hazard, such as a flood, crosses administrative boundaries. In addition, the plan should consider where specific interventions will be implemented; for example, if some interventions will focus on the elderly, data on where the majority of elderly people reside need to be available.

When interventions will be implemented, including thresholds for action. The timing of implementation of a response plan is determined by multiple factors, including the certainty in forecasts of extreme weather events (with uncertainty decreasing as the event approaches), the amount of lead time needed for implementation, and the thresholds at which specific responses are undertaken. Thresholds should strike a balance between recommending actions when they are not needed and not recommending actions when they would reduce morbidity and mortality. For example, one excess death per day during a heat wave is unlikely to be sufficient to suggest implementation of prevention programs—but at what number of deaths should actions be taken?

What interventions will be implemented. Development of an early warning system is predicated on the availability of effective interventions for reducing the burden of disease. Although there will be general interventions for the entire population, such as public-service messages on ways to lower body temperature to prevent heat stress, there should be specific messages directed toward particularly vulnerable groups, such as the elderly, the disabled, children, ethnic minorities, and low-income persons. For example, messages designed to alert parents to the risk of leaving infants unattended in automobiles during a heat wave will differ from messages designed to motivate seniors to spend time at a cooling center. These messages should be part of a larger educational program designed to increase public awareness of appropriate behavioral and other responses in the event of extreme temperatures. Stakeholders should be involved in the development of specific interventions to help ensure their maximum effectiveness.

How the response plan will be implemented. There should be a written description of how the plan (including the specific interventions that will be implemented) will work, including the responsibilities of each agency and institution involved, how information will be transmitted amongst them, back-up plans, emergency contacts, budgetary responsibilities, etc.

To whom the interventions will be communicated. The existence of the response plan, along with the interventions included in the plan, should be communicated to all potentially affected groups. The communication strategy should define who is responsible for the communication program, when the program will be initiated, who the key audiences are, the key messages to be delivered and how they should be delivered, and how the effectiveness of the communications will be monitored and evaluated (15). Tourists are often not considered in the design of response plans and communication strategies, yet they can be particularly vulnerable because language barriers make them difficult to inform about specific actions to take.

System evaluation

An essential component of a successful early warning system is an evaluation of effectiveness. This should include, at a minimum, 1) monitoring and evaluation of the overall effectiveness of the system; 2) monitoring and evaluation of the system components; and 3) an economic assessment of the cost-effectiveness and affordability of the system.

Monitoring and evaluation plan. Monitoring and evaluation of the effectiveness of the early warning system and specific interventions should be incorporated into the system design so that appropriate corrections can be made to maximize the benefits of the system while minimizing its costs. Because little is known about the effectiveness of specific interventions in reducing the morbidity and mortality associated with extreme events, research is needed to better understand where resources should be directed to achieve the most effective results.

Economic assessment of the cost-effectiveness of the system. Limited research has been conducted on the cost-effectiveness of early warning systems. Evaluation of the Philadelphia Hot Weather-Health Watch/Warning System found that the estimated costs of running the system were low compared with the estimated value of a life (26). Unfortunately, data were not available on the specific interventions included in the system, so their individual effectiveness could not be evaluated.

Much of the published information on the costs of extreme weather is focused on construction and insurance rather than adverse health events. Using a framework like that used to evaluate the cost-effectiveness of other health care interventions, decision-analytic models can be built that predict long-term costs and outcomes associated with warning systems. Models should apply best practices already recognized (34) and be highly interactive so that the cost-effectiveness of the system can be explored under different scenarios of sensitivity and specificity and should consider other sources of uncertainty. Model results should include the cost per event (e.g., death, hospitalization) avoided. Such models will leverage existing understanding of health economic modeling and enable evaluation of early warning systems to be comparable with other health interventions.

CONCLUSIONS

Evidence demonstrates that early warning systems can reduce the morbidity and mortality associated with extreme weather events. To be effective, public health must move from a focus on surveillance and response to a greater emphasis on prediction and prevention. It is essential for public health to collaborate and coordinate with meteorologists in the development of early warning systems. Linking the increasing skill of meteorologists in forecasting extreme events with effective public health interventions can improve disaster management. Projections of more frequent and more intense extreme events in a changing climate increase the importance of designing and implementing early warning systems that take into consideration the possibility of extremes outside the historic range. The
precise structure of an early warning system will depend on its purpose (i.e., whether it is designed for a heat wave or a riverine flood), on stakeholder needs, and on institutional structures. In general, such a system will include meteorologic forecasts, predictions of health outcomes, a written response plan (including thresholds for action), and evaluation criteria.

Basic research is needed to support the development of early warning systems, particularly the systematic collection of epidemiologic data on the full range of health risks associated with extreme events and better understanding of the effectiveness of particular interventions. Although extreme weather events are well known to be hazardous, the morbidity associated with these events is surprisingly poorly characterized (14). In addition, data are generally collected only for large events, so the burden of smaller events is uncertain. Functional early warning systems initiate a range of interventions in response to a warning, but few specific interventions have been evaluated for their effectiveness. Such evaluations are needed to ensure effective and efficient use of resources.

Development of early warning systems in anticipation of increased climate variability can be viewed as an application of the precautionary principle. The precautionary principle is an approach to public policy action that can be used in situations of potentially serious or irreversible threats to health or the environment, where there is a need to act to reduce potential hazards before there is strong proof of harm. One element of a precautionary approach is undertaking action before full proof of harm is available, if impacts could be serious or irreversible (35, 36). This certainly is the situation with projections of a future possibly characterized (14). In addition, data are generally collected only for large events, so the burden of smaller events is uncertain. Functional early warning systems initiate a range of interventions in response to a warning, but few specific interventions have been evaluated for their effectiveness. Such evaluations are needed to ensure effective and efficient use of resources.

Development of early warning systems in anticipation of increased climate variability can be viewed as an application of the precautionary principle. The precautionary principle is an approach to public policy action that can be used in situations of potentially serious or irreversible threats to health or the environment, where there is a need to act to reduce potential hazards before there is strong proof of harm. One element of a precautionary approach is undertaking action before full proof of harm is available, if impacts could be serious or irreversible (35, 36). This certainly is the situation with projections of a future possibly characterized by increases in the frequency and severity of extreme weather events. The scientific awareness that not only is climate change occurring now, but its effects are also being felt now, must be translated into political awareness before extreme weather events cost more lives. The time to act is now.

REFERENCES


