Background Paper on the

Benefits and Costs of Early Warning Systems for Major Natural Hazards[1]

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Submitted by

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I. Introduction and Summary

This paper surveys the benefits and costs of early warning systems (EWS) for natural hazards, and discusses issues associated with the design and implementation of early warning systems to achieve these EWS benefits.[2] The hazards considered include five meteorological hazards --cyclones, floods, heat, tornadoes, drought; and three geological hazards – tsunamis, volcanoes, and earthquakes. The primary interest of this paper is on the design and implementation of EWS in the generally less developed countries surrounding the Indian Ocean, though data from other parts of the world and discussion of institutions in the United States and Europe are used as appropriate to facilitate the analysis.

This paper draws on and is a companion piece to the background paper prepared by the Asian Disaster Preparedness Center (ADPC).[3] The ADPC paper develops several estimates of the net economic benefits from early warning systems for hazards that are common in the Indian Ocean region; two of these benefit estimates are summarized in the present paper. In addition, the ADPC paper contains a valuable discussion of political and cultural factors that may inhibit the implementation and success of early warning systems in the Indian Ocean region.

The body of the present paper is in two sections. The first, Section II, contains a discussion of the factors that drive the net economic benefits of EWS, and a discussion of how the eight hazards compare to one another with respect to these drivers of benefits. Section II concludes with some example estimates of net economic benefits for several of the more important types of hazards, and a brief discussion of approaches that have been used to make very aggregate estimate of benefits at a country-wide or even a global scale.

Section III then considers issues associated with the design of an early warning system. These include the most appropriate geographic scope for such a system, the most appropriate hazards to be included in the system, the importance of local systems that respond to hazard warnings, and issues concerning how information produced by a warning system should be made publicly available.

[2] The authors gratefully acknowledge the contributions of A.R. Subbiah and Ramraj Narasimhan of the Asian Disaster Preparedness Center, as well as those of a number of people in the World Bank, especially Apurva Sanghi and S. Ramachandran.

[3] "Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction," submitted to the World Bank Group, Global Facility for Disaster Reduction and Recovery by Asian Disaster Preparedness Center (ADPC), December 1, 2008.

Two appendices present additional detail about the likely magnitude of benefits and costs of EWS for the eight hazards, and a more detailed explanation of the hazard ranking system used in Section II.

The implications of this analysis may be briefly summarized as follows:

- Careful studies of early warning systems for specific hazards in specific locations lead one to conclude that there are important natural hazards for which early warning systems have benefits that exceed their costs, in some cases by huge margins.
- It makes most sense to focus EWS development efforts in the Indian Ocean region on the meteorological hazards (especially cyclones and floods); generally these hazards are more common and more severe, and it is within our capability to provide forecasts for these hazards with enough lead-time to allow effective responses to such forecasts.
- Forecasting systems should be structured, and institutions designed, to take advantage of efficiencies that come from including multiple hazards and covering appropriate geographic areas in the EWS.
- It will be important not only to have a good forecasting system, but also to follow-through with development of on-the-ground local response systems, so that warnings will be heeded appropriately; this may require careful tailoring of institution-building and educational efforts to the particular needs of individual countries. Accurate forecasts and appropriate local responses are both necessary in order to realize any benefits from an early warning system.

II. Benefits of Early Warning Systems for Natural Disasters

A. *Factors that Determine the Benefits of Early Warning Systems*

Warning systems provide information about possible future natural hazards, or natural disasters,[4] which may threaten injury or loss of life and damage to property. There are six factors that determine the gross benefits of a warning system.[5] The first two of these relate to the nature of the natural hazard itself:

(1) **Frequency** – is the natural hazard common or rare?
(2) **Severity** – what is the magnitude of the risk to life or the damage to property that the hazard could cause?

If a particular kind of natural hazard occurs relatively frequently, and if the warning system works, there will simply be more opportunities for that system to produce its benefits. And, if the typical severity of that kind of natural hazard is greater, the benefits of a successful warning and response are likely (but not certain) to be greater. A special challenge arises when a kind of hazard is extremely severe but very infrequent, e.g. tsunamis. In these situations, it may be difficult to sustain support for a viable warning system, and to sustain the public's readiness to respond to a warning, over the long periods between recurrences of these events.

Four additional factors jointly determine the most appropriate response when a disaster warning is issued:

(3) **Lead-time** – given when the warning is issued, what responses are possible?

Lead-time between a warning and the actual occurrence of a disaster essentially determines the range of responses that one could take – more lead-time generally means that there is a wider range of possible responses to a disaster warning.

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[4] Strictly speaking, nature creates hazards, but disasters only occur when people fail to take steps to mitigate the potential damage from such hazards. However, the term natural disaster is commonly used interchangeably with natural hazard, and that tradition will be followed in this paper.

[5] Six factors determine the gross benefits. A seventh factor, cost, which is discussed later, is required to determine the net benefits.

(4) **Accuracy** – is the warning correct?

If the warning is not very accurate, little or no response may be appropriate. On the other hand, if the warning is highly accurate, it will be rational for people to make significant and possibly costly changes in behavior.

(5) **Response Costs** – what are the costs of possible responses to the warning?

The possible responses to a disaster warning will have different costs. Relatively low cost responses are more likely to make sense than relatively high cost responses. High cost responses will make sense only when the potential disaster is severe, the warning is accurate, and the response makes a real difference.

An example of a low cost response is moving to the southwest corner of a basement when there is a tornado warning. Because lead-times for tornado warnings are just minutes, this is about the only response action that makes sense, but it is not costly. An example of a high cost response is large scale coastal evacuation in advance of a possible hurricane landfall. Depending on the population density of the threatened coastline, the cost of evacuation could be in the range of $10 million per mile of coast evacuated.[6]

(6) **Loss Reduction** -- how much are the expected costs of the disaster reduced, given the likely public response to the warning?

The loss reduction depends on the intrinsic effectiveness of possible actions that may be taken in advance of the natural disaster, as well as the anticipated degree or extent of public response to the warning.

Often the most difficult issue in assessing the likely benefits from an early warning system is predicting the actual public response that will be forthcoming when a disaster warning is issued. Ideally, one would hope that the public response to a disaster warning would be a rational expected cost minimizing response that takes into account forecast lead-time, forecast accuracy, response costs, and loss reductions. However, such rationality is difficult to achieve. Natural disasters typically threaten large numbers of people who are ordinary people not trained in the process of making optimal decisions under uncertainty, and who are almost certainly unaware of the systematic biases that plague decision-making about uncertain events, even for people with a sophisticated understanding of such decision-making. In fact, it is often a

[6] Willoughby, H.E., E.N. Rappaport, and F.D. Marks, "Hurricane Forecasting: The State of the Art," http://www.sip.ucar.edu/pdf/01_Hurricane_Forecasting_the_State_of_the_Art.1.pdf, accessed 3-6-09.

major challenge, both in planning an actual response to a warning, and in estimating the benefits of a warning, to determine what response is optimal, and how closely the actual response can be expected to approximate the optimal one.

When the people at risk from a forecasted hazard are not up to the task of making their own good decisions (e.g. whether to evacuate a coastal area threatened by a hurricane), the success of a warning system will depend importantly on how public authorities manage the response to the threatened disaster. In some countries where there is a high degree of state control over citizens, and it may be fairly easy to command an optimal response from the people threatened by a natural hazard. More often, however, the public response will be voluntary, and the tools available to public authorities will be limited to communication and persuasion as means to induce people to make a rational response to a natural disaster warning. Failure to achieve a rational public response to a disaster warning can mean that the hoped-for benefits of the warning system will be substantially or wholly unrealized.

Finally, the net economic benefits of an early warning system for natural disasters also depends on a seventh factor

(7) **Early Warning System Cost**

Obviously, if this cost is low relative to the gross benefits of the warning system, the net benefits of the system will be large, and conversely.

Many of the natural hazards that pose serious threats are meteorological, e.g. cyclones, floods, heat, tornadoes. Forecasts for hazards of this nature are produced jointly by the same weather forecasting system that also produces everyday weather forecasts of general use to the population; that system may need some upgrades to be able to forecast a particular hazard, but a substantial fraction of the system components needed for such forecasting are already in place. This has two implications. First, there is ambiguity about how much of the cost of a weather forecasting system should be attributed to forecasting a particular hazard, e.g. cyclones. Second, forecasts for meteorological hazards are joint products, and the cost of producing forecasts for all such hazards is nearly the same as the cost of producing a forecast for any single one of them. This means that it will make economic sense to produce forecasts for all the meteorological hazards if it makes sense to produce a forecast for any one of them.

B. Hazards Most Likely to Have Large Net Benefits from Early Warning Systems.

The natural hazards considered in this paper may be classified as meteorological or geological, and are listed in Table 1.

Table 1
Hazards Considered

Meteorological Hazards	**Geological Hazards**
Cyclones	Tsunamis
Floods	Volcanoes
Tornadoes	Earthquakes
Heat	
Drought	

It is not possible, within the scope of this report, to produce a definitive estimate of the total net economic benefits that would be derived from an early warning system for any one of the natural hazards in Table 1 (e.g. cyclones), much less for all of these hazards together. Making these kinds of estimates is a difficult analytical task, and for this reason, it is also rare to find estimates of these benefits in published literature on the subject of warning systems for natural hazards.

However, a general survey of what is known about these hazards was conducted, with the aim of assessing each hazard in terms of the seven determinants of early warning system benefits that were discussed in Section A above. The results of the survey are presented as Appendix 1 to this report.

We divide this section into two parts. In the first, we present a summary ranking of hazards by the likely (gross) benefits that might be derived from an early warning system. In the second section we discuss the likely costs of early warning systems, which is the second element of the net benefits of such a system.

1. The Benefits of Early Warning Systems for Hazards

Many factors determine the benefits of early warnings systems for the various natural hazards; Appendix 1 surveys each of the natural hazards and discusses the factors that drive benefits for each hazard. However, comprehensive and consistent benefit estimates for each natural hazard do not exist. Thus, we are forced to adopt a more subjective approach in forming a judgment about the likely relative benefits obtainable from early warning systems for each of the possible hazards. To structure the process of forming such a judgment, we developed a hazard scoring system, described below. We do not claim that this is any more than a reasonable and systematic way to go about forming a judgment about which hazards are likely to have high net benefits from an early warning system.

To develop a subjective scoring system, we first observe that, in order for the benefits of an early warning system to be high, a natural hazard must simultaneously satisfy several criteria: it must be frequent, severe, predictable with reasonable lead-time and accuracy, and there must exist cost-effective responses to warnings of an impending occurrence. If any one of these criteria is not met, the potential benefits from a warning system may be small or even zero. For example, if the hazard is not predictable, it does not matter how frequent, severe, or cost-effective responses to warnings might be --- if one cannot predict the hazard, the benefits of an early warning system will be zero.

The above implies that one might assign numerical scores to each determinant of benefits for each hazard, and then combine these scores for each hazard, using a geometric average. Geometric averaging means that if the score for one or more determinants of value is zero or near zero, then the geometric average will also be zero or near zero, regardless of what the scores might be for the other determinants of benefits.

Thus, the subjective scoring system used here assigns a score from 0 to 5 to represent the degree to which a particular hazard meets the criteria of being frequent, severe, predictable, and has cost-effective responses. These scores from individual determinants of benefits are then combined using a geometric average to arrive at an overall summary score for the hazard. Obviously, these scores ultimately rest on the quality of the expert judgments on which they are based.

Hazards sometimes differ significantly in the extent to which an early warning system saves lives vs. protects property. An extreme example is heat, which is a surprisingly severe hazard, even in the developed world, if the consequences are measured as lives lost; whereas, if the consequences are measured as property damage, the severity of heat is minimal or non-existent. Thus, we apply the scoring system twice – once when the criterion is lives saved, and again when it is property losses reduced. The summary rankings of the hazards change in reasonable ways, depending on which criterion is used. Table 2 presents the results obtained using this subjective scoring system.

For a detailed discussion of the reasoning behind the numbers in Table 2, please see Appendix 2. Here we provide some more general observations about the rationale for, and implications of, the numbers in Table 2.

The hazards for which an early warning system is believed to have the highest benefits are cyclones, floods, and volcanoes, whether one looks at the criterion of lives saved or property loss reduced. A common characteristic of these hazards is that we have the ability to predict them quite well, with at least a few days lead-time (except for flash floods, a subset of all floods, for which the lead-time may be only minutes). With a few days lead-time, it is possible to have orderly evacuations that protect all lives potentially at risk, and to a lesser extent, it is possible to take steps that modestly reduce property damage.

Extreme heat is a hazard that has a relatively high benefits ranking, when the criterion is saving lives, but a low ranking when the criterion is reducing property losses. This is not surprising, in that heat threatens lives but not property.

Tsunamis fall in the middle of the range, by either the lives saved criterion or the loss prevention criterion. Most importantly, this is because tsunamis are uncommon in the Indian Ocean region. The tsunami of 2004 was the kind of event that might happen once every 100 years. In contrast, Bangladesh and India suffered nearly 300 cyclones, in the time period from 1900 to 2008.[7]

Drought is in the middle or lower middle of the range, depending on the criterion used. Droughts are not especially common, not really predictable, not really life threatening (if relief is provided), and there is not that much that can be done if a warning were made available.

Tornadoes rank close to the middle of the range on the lives saved criterion, but at the bottom of the range using the loss prevention criterion. They rank so low on loss prevention because warnings have very short lead times, allowing no opportunity to do anything but move to a safer location.[8]

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[7] EM-DAT, The OFDA/CRED International Disaster Database – www.emdat.net – Universite catholique de Louvain – Brussels – Belgium.

[8] About 75 percent of the world's reported tornadoes occur in the mid-section of the United States. This is no doubt partly the case because that region of the world is intrinsically prone to generating tornadoes. However, it may also be partly true because tornado detection and reporting is highly developed in the United States. Still, tornadoes do occur in other parts of the world.

Earthquakes rank at the very bottom of the list of hazards, by either criterion. This is simply because we are presently unable to predict earthquakes. So an early warning system is not a possibility.

Table 2
A System for Scoring Hazards by Their Likely Benefits – Indian Ocean Region

Scores by Life Saving Benefits	Frequency	Predictability	Severity (loss of life)	Potential Life Saving	Summary
Cyclones	5	5	4	5	4.7
Floods	5	5	2	3	3.5
Volcanoes	2	5	3	5	3.5
Heat	3	5	2	3	3.1
Tsunamis	1	3	5	4	2.8
Tornadoes	2	3	2	3	2.4
Drought	2	2	1	1	1.4
Earthquakes	3	0	5	0	0.0

Scores by Loss Prevention	Frequency	Predictability	Severity (damage)	Potential Loss Reduct.	Summary
Cyclones	5	5	4	3	4.2
Floods	5	5	5	2	4.0
Volcanoes	2	5	2	3	2.8
Drought	2	2	3	1	1.9
Tsunamis	1	3	3	1	1.7
Tornadoes	2	3	2	0	0.0
Heat	3	5	0	0	0.0
Earthquakes	3	0	4	0	0.0

2. The Costs of Early Warning Systems

The preceding section presented an assessment of the benefits of early warning systems for five meteorological hazards and three geological hazards. In this section, we consider the cost of early warning systems, which is the other element of the net economic benefit of these systems.

A key issue is the extent to which warnings for hazards are produced from the same system, or perhaps from somewhat different but related systems that share common components. When there is sharing of some or all components of a forecasting/warning system, it is likely to be cost-effective to design an early warning system that encompasses all the hazards that share systems or system components.

The obvious case here involves the meteorological hazards, e.g. cyclones, floods, heat. These hazards are predicted by some kind of weather forecasting system, most likely the same system that is used to produce routine weather forecasts for a given region. Since a routine weather forecasting system is typically already in place in most countries of the world, that system may need only slight upgrades to be useable in predicting meteorological hazards. When this is the case, the relevant cost to assign to prediction of the hazard is only the additional cost (if any) that may be required in order for the existing weather prediction system to be upgraded as necessary to forecast the hazards.

Furthermore, it is likely that the upgrades necessary to forecast any one meteorological hazard (e.g. cyclones) will also make it possible forecast other meteorological hazards (e.g. floods). Thus the additional costs involved in bringing all the meteorological hazards into the prediction repertoire may not be much more than the costs of bringing any one of them in. Therefore, if the incremental costs of upgrading a weather forecasting system to predict one hazard are justified by the benefits of doing so, then it will likely make sense do whatever upgrading is required to predict all the meteorological hazards as a group.

The costs of systems to predict meteorological hazards can be reduced by designing collective systems operating over an appropriate geographic scale. This topic is explored in more detail in the following section, which uses Europe and the RIMES system in Thailand, as examples that show how certain elements of an advanced forecasting system need not be duplicated in each country, but can be funded collectively and the resulting information shared by all the countries within a geographic region. Taking advantage of these kinds of economies of geographic scope can further reduce the cost to each participating countries of having access to an advanced system for forecasting meteorological hazards.

Geological hazards are somewhat different from meteorological hazards. To start with, there really is no system that can predict earthquakes. However, we do have systems that monitor earthquakes, and the ability to monitor earthquakes is one element of systems that predict tsunamis and of systems that predict volcanoes.

Until recent years, earthquake monitoring was the primary way in which tsunamis were predicted. Predictions were made based on the magnitude and location of detected earthquakes. On rare occasions, an earthquake is so strong (e.g. magnitude 9, like the quake that generated the 2004 Indian Ocean tsunami) that a tsunami will almost certainly occur. More commonly, however, the detected earthquake will be of a lesser magnitude, and the creation of a tsunami will not be a certainty. For this reason, tsunami warnings in the past were plagued by false alarms.

In recent years, an advanced system for real-time monitoring of sea level in the open ocean has been developed. This system allows for direct detection of a potential tsunami wave, and it is expected that this system will significantly improve the accuracy of tsunami predictions.

The instruments for detecting earthquakes are sufficiently sensitive, and there are enough of them around the world, that it is virtually impossible for an earthquake to go undetected, no matter where in the world it occurs. This means that it would be possible to predict tsunamis, in the old way based on earthquake detection, anywhere in the world. The 2004 Indian Ocean tsunami, for example, could have been predicted this way, and since the causative earthquake in that case was so powerful, there would have been high certainty of a tsunami, even absent any confirmatory system to detect the actual wave in the open ocean. However, when earthquakes are less powerful, tsunami prediction solely from earthquake monitoring would be subject to a high rate of false alarms.

This means that accurate tsunami prediction (except perhaps in rare instances of a magnitude 9 or higher quake) depends on having these advanced systems for measuring sea level in the open ocean. The sole use of these systems is in detecting tsunamis, and so they have no spillover benefits in predicting other hazards.

The initial indication of a possible volcanic eruption also comes from earthquake monitoring. If a quake is detected near a potentially active volcano, this is an indication that an eruption may occur in the near future. In the case of recent major eruptions, the first seismic indications were received about a year in advance of the actual eruption. When an eruption is suspected in the near term, the prediction process involves placing instruments on the volcano to measure any ongoing seismic activity and any possible ground deformation that would suggest rising pressure from magma underground. As with tsunami prediction, the prediction of a volcanic eruption involves specialized activities that do not have spillover benefits in predicting other hazards.

The foregoing considerations suggest that the costs of predicting meteorological hazards will be relatively low, especially on a per-hazard basis, as the same prediction system can serve to warn of multiple hazards. On the other hand, for geologic hazards, the predictive systems are specialized to each hazard (deep ocean monitoring for accurate tsunami prediction, on-site instrumentation for volcanic eruption prediction). This means that the costs of prediction are not shared in the same way for geologic hazards, and costs will be higher on a per-hazard basis.

C. Example Net Benefit Estimates

In this section we present some estimates of benefits from early warning systems. Two of these examples, which come from published literature, pertain to tornadoes, extreme heat, hurricanes in the United States. The other examples are for cyclones and floods in Bangladesh. This section concludes with a discussion of highly aggregate approaches that have been used to create country-wide or even world-wide estimates of the net benefits of weather forecasts.

1. Examples from the United States

During the 1990s, the United States National Weather Service installed Doppler radar systems which increased the fraction of tornadoes for which a warning was provided from 35 percent to 60 percent, and increased the average warning lead-time from 5.3 minutes to 9.5 minutes. Simmons and Sutter[9] analyzed 15000 tornadoes in the U.S. from 1986 to 1999, during which time the Doppler radar systems were progressively installed throughout the United States. Controlling for tornado characteristics and path, these researchers found that the use of Doppler radar reduced fatalities by 45 percent and reduced injuries by 40 percent. These reductions translate into averages of 79 deaths prevented per year, and 1052 injuries prevented per year.

Simmons and Sutter do not go the next step and place a dollar value on these saved lives. However, the concept known as the "value of a statistical life" is frequently used in evaluating policies that provide benefits in the form of reduced mortality for large populations. The United States Environmental Protection Agency, for example, uses a value of $6 million per life saved in decisions about reducing pollution, notably air pollution. If this kind of number were applied to the prevention of 79 deaths per year, the value of this prevention would be about $500 million per year. This figure does not include the value of prevented injuries, nor does it include benefits from other uses of Doppler radar (e.g. improving flash flood warning capabilities, where lead-times increased from 14 minutes to 54 minutes)[10]. The cost of installing this radar system was $1.5 billion.[11] Assuming a 20-year useful life of this radar system, and a 5 percent rate of

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[9] Simmons, Kevin M., and Daniel Sutter, "WSR-88D Radar, Tornado Warnings, and Tornado Casualties," *Weather and Forecasting*, Vol. 20, No. 3, June 2005, pp. 301-310.

[10] NOAA Celebrates 200 Years of Science, Service, and Stewardship, accessed February 9, 2009 at http://celebrating200years.noaa.gov/breakthroughs/tornadowarnings/welcome.html#improved .

interest, the present value of these benefits is about $6 billion, or about 4 times the cost. Thus, even if deaths from tornadoes were the only benefit from a tornado warning system, the cost of this system is easily justified by the deaths it apparently prevents.

A second example from the United States analyzed extreme heat in the city of Philadelphia over a four year period from 1995 to 1998.[12] During this time period, a system for issuing warnings of dangerous heat waves and responding appropriately was instituted in Philadelphia. Responses to warnings included actions such as these: radio and television announcements warning of the danger and informing of appropriate steps to reduce the risk, encouragement of "buddy systems" to check on vulnerable neighbors, staffing a "heat-line" to field questions, extending operating hours for air-conditioned senior centers, adding shifts for emergency medical teams. Many of these actions have no direct cost (relative to the costs that would have existed without a heat wave warning). The actions that do have direct costs, such as wages for extended hours for the "heat-line" and emergency medical staff, appear to have been less than $10,000 per day, or a total of $210,000 for all the days in Philadelphia study in which a warning was in effect.

This study estimated that 117 lives were saved by heat wave warnings during this period of time. This savings of lives was valued at $500 million, using a value of a statistical life slightly lower than the EPA's $6 million. Nevertheless, the heat wave warning system had an overwhelmingly high excess of benefits over costs.

The third study from the United States estimates the reduction in losses from hurricanes by comparing actual losses to the losses one might have expected given the growth in population and increase in the value of property along hurricane-prone coastlines. [13] This study estimated that hurricane deaths each year are lower by about 219, relative to what one would have expected. These 219 prevented deaths are value at $10 million per life (a relatively high valuation, even for the United States). This implies about a $2 billion annual benefit of saved lives, presumably attributable to hurricane early warning systems.

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[11]"National Weather Service and Fleet Modernization Issues," Testimony of Joel C. Willemsen and L. Nye Stevens before the House Subcommittee on Energy and Environment, February 24, 1999, accessed February 8, 2009 at http://www.gao.gov/archive/1999/a299097t.pdf .

[12] Ebi, Kristie L, et. al., "Heat Watch Warning Systems Save Lives: Estimated Costs and Benefits for Philadelphia, 1995-1998," *Bulletin of the American Meteorological Society*, August 2004, pp. 1067-1073.

[13] Willoughby, H., HRD/AOML, "Costs and Benefits of Hurricane Forecasts," minutes of 55th Interdepartmental Hurricane Conference, 5-9 March 2001, Orlando, FL.

Regarding property damage, it is estimated that losses are lower by about $1 billion per year, relative to what one would expect, given the increase in value of property located along threatened coastlines. Thus the total benefits of hurricane warning systems are estimated at $3 billion, with 2/3 of this coming from lives saved, and 1/3 from reduced property damage.

Finally, the costs of hurricane warning systems are estimated using an evacuation cost per mile of $0.5 to $1.0 million per mile, times 300-400 miles, times 3 landfalls per year, producing an average annual evacuation cost of about $825 million. To this is added an estimated $85 million annual cost of producing the hurricane forecasts. Overall, this implies that the ratio of benefits to costs is about 3 to 1, for hurricane warning systems in the United States.

It should be noted that hurricane losses tend to be significantly influenced by extreme events that occur only a few times a century, and the analysis in this paper was done before Hurricane Katrina. It is possible that the inclusion of Katrina would substantially lower the apparent reduction in hurricane death rates, and hence hurricane benefits, that is estimated in this paper.

2. Examples from Indian Ocean Region[14]

Cyclones are quite common in the Indian Ocean region. In November 2007, Cyclone Sidr struck the coast of Bangladesh as a category 4 storm. It is estimated that about 3400 people were killed by this storm, and that more would have been lost except for certain disaster prevention measures, including an improved forecasting and warning system. Total monetary damages from this storm were estimated to be US$ 1.7 billion.

If there had been an advanced numerical weather prediction system in use, forecast lead-times could have been extended to 5 days, and the areas at risk of heavy rainfall and strong wind could have been identified with greater accuracy.[15] It is estimated that the costs (fixed plus variable) of such a system, over a ten-year period, would have totaled about US$ 3.1 million.

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[14] The examples in this section come from "Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction," submitted to the World Bank Group, Global Facility for Disaster Reduction and Recovery by Asian Disaster Preparedness Center, December 1, 2008.

[15] Numerical weather prediction refers to direct modeling of the behavior of the atmosphere using fluid dynamic and thermodynamic equations. Absent numerical weather prediction modeling, forecasts are made from a weather observations (pressure, temperature, humidity), using statistical relationships that reflect weather regularities, and forecaster judgment.

Had a weather prediction system like this been in place, it is estimated that the monetary damages from Cyclone Sidr would have been reduced by US$ 79.14 million. This reduction would have been achieved through early harvesting of some crops, and fish, and shrimp, and by reduced losses of household possessions, agricultural equipment, fishery equipment, livestock, and equipment and furniture in offices and schools. In addition, there would have been further reductions in the loss of human life and reductions in the general suffering of the population, but these cost reductions are excluded from this calculation.

The estimated 10-year system cost (US$ 3.1 million), and estimated damage reduction (US$ 79.14 million) were used in a probabilistic analysis to estimate the expected net benefits, over a 10-year period, of having this improved weather forecasting system in place. This estimate assumed a return period of 5 years for such a storm, and a forecast error probability of 10 percent. The expected benefits of the enhanced warning system were estimated to be about US$ 78 .9 million, or about 25 times the 10-year cost of US$ 3.1 million.

The second example from the Indian Ocean region is flooding in Bangladesh. Floods in Bangladesh are common annual occurrences, though the exact timing and extent of flooding is variable from year to year. To estimate the benefits of an early warning system, the possible savings from an early warning for the floods of 2007 were estimated. As with Cyclone Sidr discussed above, the sources of these benefits were early harvesting of crops, fish, and shrimp, and prevention of losses of moveable assets, including livestock. It was estimated that an early warning system for the 2007 floods would have reduced damages by US$ 207.9 million.

The floods of 2007 were moderate, with a return period of 5 years. To estimate the cost savings for floods of other magnitudes and return periods, the 2007 flood damage reduction was scaled up, by as much as a factor of 8 for 50-year floods, and down by a factor of 0.25 for common annual floods.

The cost of providing flood warnings was the same US$3.1 million value used for the Cyclone Sidr analysis above. Note that this is a case where a single forecasting system produces benefits for multiple hazards.[16] That the full $3.1 million cost is charged to both the cyclone and flood forecast benefits means that the net benefits of both systems are understated, though by a small amount in percentage terms.

As in the Cyclone Sidr case, the benefits were used in a probabilistic analysis to estimate the expected benefits, over a 10-year period, of having an early warning system in place. The probabilistic analysis included floods of 5 possible sizes and return periods (1-year, 5-year, 10-year, 30-year, and 50-year), and it incorporated a forecast error probability of 10 percent. The

[16] This issue was mentioned earlier in Section IIB2, and is taken up in more detail in Section III.

analysis produced total expected benefits, over a 10-year period, of about US$ 1700 million, which is more than 500 times the 10-year system cost of US$ 3.1 million.

3. Aggregate Approaches to Estimating Benefits

An analysis presented at a 1994 WMO conference proposed that the benefits of weather forecasts exceed costs by a factor of 5:1 or 10:1, on average. National meteorological service (NMS) budgets at the time were about US$ 4 billion, implying that the annual benefits of NMS would be US$ 20-40 billion.[17]

As suggested by the specific examples discussed earlier in this section, the ratio of benefits to costs for early warning systems is extremely variable –3:1 for hurricane warnings, 4:1 for tornado warnings, 25:1 for cyclone Sydr, 500:1 for Bangladesh floods, 2500:1 for Philadelphia heat waves. These examples do not suggest that an overall factor of 5:1 or 10:1 is unreasonable, but they do indicate that there is a great deal of uncertainty about the true (weighted average) ratio of benefits to costs.

A second kind of approach to estimating aggregate benefits of early warning system starts from an estimate of the damages of natural disasters and then relies on expert judgments of the degree to which these losses would be reduced if there was a warning system (or a better warning system). This approach underlies the benefit estimates discussed above for Cyclone Sydr and Bangladesh floods. In those estimates, the estimated damage reduction was combined with explicit estimates of the prior probabilities of hazards, and of the probabilities of forecast errors, to arrive at the final expected benefit numbers.

A much more aggregate version of this approach was used in assessing the benefits of modernization of the Russian Federation Hydromet Service.[18] That analysis began with estimates, by economic sector, of the annual average damages from weather hazards (which estimates should reflect the frequency of such hazards). Then experts in each sector were asked to assess how much those damages would go down, and how much response costs would change, as a result of improved weather forecasts. These assessments would implicitly incorporate judgments about the probabilities of forecast errors (both failure to forecast an

[17] Cited in "Weather and Climate Services in Europe and Central Asia," World Bank Working Paper No. 151, World Bank, Washington DC, June 2008.

[18] "Project Appraisal Document on a Proposed Loan in the Amount of USD 80 Million to the Government of Russian Federation for a National Hydromet Modernization Project," World Bank, October 12, 2004, pp 85-89, cited with permission.

event and false alarms). The estimated benefits of Hydromet modernization were US$ 0.5-1.0 billion over a seven year period, implying a benefit-cost ratio between 5:1 and 10:1.

III. Design of Early Warning Systems

A. Scope of Hazards Covered

There are advantages to early warning systems that deal with multiple related hazards. One way that multiple hazards can be related is if they use some or all of the same system components. In this case, it may be most efficient to have a warning system that covers all the hazards that share system components. The shared components may be in systems required for forecasting hazards, or they may be in systems required for responding to hazard warnings at the local level.

The most obvious example where common systems provide forecasts of hazards is meteorological hazards, for which a general weather forecasting system provides the foundation needed to make predictions of all meteorological hazards. In addition, weather forecasting systems provide other benefits, such as routine weather forecasts used by businesses and the general population for planning activities affected by the weather. If forecasting systems already exist for routine weather prediction, the cost of enhancing those systems to provide early warnings of weather hazards is smaller than if the entire system for forecasting hazards needed to be developed from the ground up.

Another example of shared systems for forecasting hazards is in geologic hazards. Here the capability to monitor and interpret seismic activity is a shared component of systems that predict volcanic eruptions and systems that predict tsunamis. As was discussed in section II,B,2, however, the additional components of systems to predict tsunamis (deep ocean sea level monitoring) and volcanoes (on-site seismic instrumentation) are not shared systems.

Another kind of overlap may exist in developing local institutions and procedures for executing a response to a warning. For example, the institutions and procedures for responding to a cyclone warning or a tsunami warning would both be concerned with evacuation of coastal populations. Not all the procedures would be identical for these two hazards, however, since moving to safety in the case of a cyclone might mean moving a certain distance inland, whereas moving to safety in the case of a tsunami might mean moving to a location a certain distance above sea level.

B. Geographic Scope

1. Meteorological Hazards

As was discussed in the preceding section, forecasts of meteorological hazards are produced using a common weather forecasting system. Modern systems for forecasting weather depend on observations that may be obtained from satellites, airplanes, weather balloons, ocean observing stations, and ground observations. These observations are processed in very computationally intensive computer models. These computer models sometimes are used to represent weather in relatively large geographic areas over relatively long periods of time (e.g. 10 days), albeit at a coarse spatial resolution. Such models may then provide "boundary conditions" used in running other models that focus in on smaller geographic regions, for a shorter time period (a few days), but at a more detailed spatial resolution.[19] Finally, in the United States, at least, the local forecast outputs from these computer models may be modified by meteorologists based on their judgment and experience with those model outputs and the past weather behavior in the local region for which they are responsible.

As the foregoing description suggests, different components of a weather forecasting system operate over different geographic (as well temporal) scopes. How the developed European countries have dealt with these issues suggests what may be proper geographic and temporal scopes for the various elements of weather forecasting systems. It is useful, therefore, to summarize how weather forecasting is done in Europe.

Europe has three system components that are used for region-wide data gathering and analysis. One of these is the system of weather satellites that includes geo-stationary satellites which cover the entire European region, and polar satellites which are able to make observations for the entire northern hemisphere, and which are used in cooperation with the United States National Oceanic and Atmospheric Administration (NOAA). Another component is an ocean observing system, which is also run in cooperation with NOAA. The third component used on a region-wide scale is a computer model that produces 10-day forecasts, at a coarse spatial resolution, for the entire region that contains the participating countries.

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[19] Forecasting drought is done differently, since the time frame for drought forecasts is months rather than days. Traditionally, drought forecasts have been generated by time-series analysis, essentially sophisticated extrapolation methods. See Kim, Tae-Woong and Juan B. Valdes, "A Non-linear Model for Drought Forecasting Based on Conjunction of Wavelet Transforms and Neural Networks, 5-15-2003, http://www.u.arizona.edu/~jvaldes/Fcst_Asce_Final.pdf accessed 3-6-09.

There are about 30 countries that participate in these cooperatively run systems. These countries range from Norway to Morocco, and Ireland to Turkey.[20] They share the costs of these systems in proportion to their country's GDP. The budget for the satellite systems is about US$ 380 million,[21] while that for the region-wide weather forecasting model is about US$ 50 million.[22]

The region-wide weather forecasting model provides longer term (i.e. 10-day) forecasts for all the participating countries. It also provides boundary conditions that are necessary to run shorter-term forecasting models that are geographically more focused. Some of the larger participating countries, e.g. France, Germany, Italy, and UK, have their own national weather forecasting services that run these more detailed models. Other participating countries have formed consortia that provide these services for the subset of participating countries that cooperate in this way. A prominent example of this is the HIRLAM (High Resolution Limited Area Model) sponsored by Denmark, Estonia, Finland, Iceland, Ireland, Netherlands, Norway, Spain, and Sweden. The HIRLAM group explains the typical forecasting process for European countries in the following succinct way:

> "National Meteorological Services (NMS) are required to provide short and medium range weather forecasts, warnings and alerts for their territory. For medium range forecasts one needs to use global models. Most European NMSs use the products from ECMWF [Note: this is the European Center for Medium-range Weather Forecast, the organization that produces the 10-day forecasts]. For short range applications it is most cost effective, and even necessary, for very high resolution, to run the NWP [Numerical Weather Prediction] systems for only a small part of the globe using a Limited Area Model (LAM). These LAMs require boundary conditions from global models, like the ECMWF model."[23]

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[20] European Center for Medium Range Forecasts, Member Countries Graph and List, http://www.ecmwf.int/about/funding/index.html , accessed 3-4-09.

[21] EUMETSAT 2008/2009 Budget Review, http://ec.europa.eu/budget/reform/library/contributions/o/20080505_O_12.pdf, accessed 3-4-09.

[22] European Center for Medium Range Forecasts, Member Countries Graph and List, http://www.ecmwf.int/about/funding/index.html , accessed 3-4-09.

[23] Hirlam website, "Documents" tab, http://hirlam.org/ accessed 3-4.09.

The way the European countries have gone about the division of weather forecasting tasks suggests that for the Indian Ocean region, certain task should be undertaken collectively by a single organization. This organization might usefully participate with the Europeans, or even the United States, in satellite and ocean observing systems. It could also be responsible for producing a coarse resolution long term forecast for the entire region, similar to the one that is produced by the Europe-wide consortium for Europe. Some of the large countries (e.g. India) might then take responsibility for producing more finely resolved forecasts for their countries, while other smaller or poorer countries would likely find it advantageous to form cooperative agreements along the lines of HIRLAM.

2. Geological Hazards

The geologic hazards are earthquakes, tsunamis, and volcanoes. Earthquakes are essentially unpredictable at the present time. The geographic scope for tsunami prediction is clearly identifiable as the coastline that is potentially affected by the occurrence of an earthquake that may create a tsunami. In the case of an earthquake that creates a tsunami in the Indian Ocean, the geographic scope would include the west coast of Australia, the Indonesian islands, the south Asian coast, the east African coast, and a number of islands within the Indian Ocean.

The geographic scope for volcano prediction is the entire world. This is because the science of monitoring volcanoes is similar for volcanoes anywhere in the world. The most common situation when seismic activity suggests a possible volcanic eruption is to send a team of scientists to the volcano to set up monitoring equipment to track the seismic activity and ground movement associated with an impending volcanic eruption. This is a feasible approach because the first indications of a possible eruption commonly occur about a year before the eruption itself occurs. Although volcanic eruptions are not high on the list of natural hazards, these observations suggest that the most efficient approach to providing early warnings for volcanic eruptions might be a collective system that encompassed the entire world.

C. The RIMES Example

The 2004 tsunami in the Indian Ocean provided a catalyst to create an organization known as the Regional Integrated Multi-Hazard Early Warning System (RIMES).[24] This is a collective effort involving 26 countries mostly located on the Indian Ocean to provide early warnings of

[24] For more detail about RIMES see "Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction," submitted to the World Bank Group, Global Facility for Disaster Reduction and Recovery by Asian Disaster Preparedness Center, December 1, 2008.

future tsunamis as well as early warnings for weather hazards such as cyclones. While the original impetus for forming this organization no doubt came from the devastating 2004 tsunami, the inclusion in the system of weather hazards has created broader interest in participation, since these weather hazards are far more common that tsunamis, and for a few of the participating countries, tsunamis are no threat at all.

There may be some efficiency gain in combining tsunami prediction with weather hazard prediction, though this may not be huge, since the systems required for tsunamis and weather hazards do not have many common components. There may be more synergy, however, in the efforts RIMES makes to help its participating countries plan at the local level for response to possible future warnings. There are certainly cases, such as evacuation of coastal populations, where the local response to a warning is similar for a tsunami threat and a cyclone threat, for example.

D. The Role of Local Response

It is possible to gain efficiencies from collective systems to predict natural hazards. However, such predictions create no benefits unless there is an appropriate response, and the appropriate response is largely something that takes place at the local level.

The mechanics of responding to warnings are likely to be somewhat different depending on the lead-time between issuing a warning and the occurrence of the actual event. For some of the most important hazards (e.g. cyclones, river floods, heat), this lead-time is measured in days, or up to a week or so, if one also counts the time during which the hazard has become a real possibility but is not yet a well-defined threat. This is sufficient time to communicate the danger through conventional mass media channels such as television, radio, and newspapers, and also to prepare both citizens and local authorities to be ready to act quickly, if and when the possible hazard becomes a real threat.

Even if a threat is successfully communicated with enough lead-time for people to take action, it is not always easy to get the appropriate response from the people who are in danger. In the case of the Nargis cyclone in Myanmar in 2008, a warning was communicated through state-run television, and on the ground by military personnel, starting about 48 hours before the cyclone hit. However, apparently as a result of general mistrust of the government , these warnings went unheeded by many. As a result, about 138,000 people lost their lives in that cyclone.[25]

[25] EM-DAT, The OFDA/CRED International Disaster Database – www.emdat.net – Universite catholique de Louvain – Brussels – Belgium.

Another potential impediment to appropriate response is the view, in some parts of the world, that natural hazards are "Acts of God." With this perspective, people adopt a fatalistic attitude, believing that they cannot really control what happens to them, so they might as well simply accept what comes their way.[26]

In other parts of the world, such as Cuba, responses to cyclone warnings are exemplary. This may be due to a political system with a high degree of control over the population and/or to the presence of a relatively well educated population and neighborhood organizations that are readily mobilized to produce a coordinated response to emergencies.[27]

These examples indicate that there is a certain amount of ground-work that must be in place for warnings, even with adequate lead-time, to elicit the appropriate response. This ground-work is presumably an educational process, but one that would likely need to be tailored specifically to each country's or region's individual situation.

Other threats, like tornadoes and flash floods, usually have lead-times measured in minutes. For these kinds of hazards, having a specialized communication system in place is probably of central importance. This might be a system of sirens that could be heard throughout any populous region that might be threatened by one of these hazards. One can also send local police through neighborhoods using loudspeakers to get the word out, especially if there are no sirens in place, or the local population needs additional coaching in how to respond to respond the threat ("tornado coming, move immediately to southwest corner of the basement or to a windowless interior room on the first floor"). Conventional radio and television could also be used, but this will not necessarily reach everyone in just the few minutes that might be available before the hazard occurs. In the United States, one can also buy a NOAA weather radio that is capable of responding, with an audible alarm, to National Weather Service warnings even if the audio on the radio is turned off. On hearing the alarm, the user may then turn on the audio to hear the nature of the warning. These radios can be programmed to respond only to those alarms that are relevant to the radio's user.

Accurate forecasts and well-developed local response capabilities are highly complementary; if either one is deficient, the promised benefits of an early warning system will not be realized. In the cases of hazards for which accurate forecasts are possible, it may be relatively easy to re-produce the forecasting technology in another part of the world. Developing local institutions that reliably produce appropriate local response to warnings may

[26] "Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction," Asian Disaster Preparedness Center, December 1, 2008.

[27] "Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction," Asian Disaster Preparedness Center, December 1, 2008.

be the more difficult problem that must be overcome if the benefits of early warning systems are to be realized.

E. Information as a Public Good

Information of any sort tends to have some of the characteristics of a public good, insofar as information can be distributed widely at little or no cost, once it has been produced, and the societal benefits from the information that has been produced are generally maximized if the information is made available as widely as possible. This means that the net economic benefits of information are maximized if the information is freely provided to anyone who wants it.

All of this applies to information generated by an early warning system for natural hazards. In the context of early warning system information, it is important to recognize that it is not just the warning itself that is a public good, but also the various kinds of raw information that go into the modeling systems used to produce forecasts, and the unedited information that comes out of those modeling systems. Making these primary and intermediate types of information available creates additional opportunities for people or organizations to produce their own specialized kinds of forecasts that satisfy their own specialized needs. These kinds of forecasts may be produced by simple further processing or alternative processing of the original data, or by augmenting the original data with other specialized data. By making the original data available, one encourages the development of additional uses for the data, and the realization of additional societal benefits from those uses. With the development of the internet in recent years, the costs of data distribution have declined to almost nothing, and the potential for creative uses of information have expanded dramatically.

However, there is always a tension here because of the so-called "free-rider" problem. If people know that forecasts and data will be made available for free, they will not be willing to contribute to the original cost of creating that data. In a large region, such as the United States, with a unified government, it is a simple matter to fund the original creation of data from tax revenues, and then distribute the information freely to the citizens whose tax money was used to create the data in the first place.

The free-rider problem may be more difficult for a collective system sponsored by multiple countries. In this case, there will be an incentive for individual countries to avoid contributing to the system, if they can expect to receive the information produced by the system for nothing after it has been produced. While there is no perfect solution to this problem, it may not be a major stumbling block to free distribution of information if the larger countries can be persuaded that the widespread benefits of free information distribution outweigh the inequities that free distribution creates in who pays for the creation of the data in the first place.[28]

[28] One could require countries to participate in an early warning system as a precondition for receiving international aid in the event of a disaster. However, it would be very hard to actually follow through on the threat to deny aid to a non-participating country.

IV. Appendix 1: Survey of Natural Hazards

A. Meteorological Hazards

Natural disasters caused by weather include tropical cyclones (hurricanes), tornadoes, floods, heat waves, and droughts.

1. Tropical Cyclones or Hurricanes

Tropical cyclones, or hurricanes, as they are called in the United States, are large storms which form over warm ocean waters in the tropics or sub-tropics. They tend to occur seasonally – for example, Atlantic hurricanes affecting the United States are concentrated in late summer and early fall. Hurricane damage occurs as a result of powerful winds, flooding (from coastal storm surge and heavy rainfall), and tornadoes that may be spawned by the hurricane.

Hurricanes in the United States are classified as category 1 through category 5 on the Saffir-Simpson Scale. Typically, evacuation of coastal areas in a hurricane's path is ordered for storms of category 3 and up. A category 3 hurricane has winds of 111 to 130 miles per hour, with a storm surge of 9-12 feet; a category 5 hurricane has winds of 155 miles per hour or more and may bring a storm surge that is 18 feet above normal.[29] Category 3 and up storms are responsible for about 85 percent of the total monetary damages attributed to hurricanes.[30]

a) **Frequency** and **Severity**

Hurricanes are quite common. In the United States, one or two will make landfall each year. However, the frequency of occurrence at any specific location is much lower. Of major United States metropolitan areas, the Miami area in south Florida, is perhaps the most likely site of a hurricane landfall, with a category 3, 4, or 5 storm expected about once every 5 years.[31] In New

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[29] http://www.nhc.noaa.gov/aboutsshs.shtml .

[30] http://sciencepolicy.colorado.edu/admin/publication_files/resource-2476-2008.02.pdf.

[31] In Miami, landfall for category 3, 4, or 5 hurricanes is one every 9, 16, or 33 years. So 1/9 + 1/16 +1/33 is the probability of a category 3 or 4 or 5 in each year. This sum is .20, implying a 1 in 5 chance each year. Return period data is from http://www.nhc.noaa.gov/HAW2/english/basics/return.shtml.

Orleans, which suffered the devastating Hurricane Katrina in 2005, a category 3, 4, or 5 storm would be expected about once in 20 years.[32]

Hurricanes can be very severe natural disasters. In the United States, Hurricane Katrina in 2005 was the most costly natural disaster ever in terms of monetary damages, estimated at $125 billion dollars. In terms of loss of life, Katrina was the fourth worst disaster for the United States, with 1833 deaths. However, there is reason to think that this death toll need not have been so high if planning and public response had been more appropriate to the threat posed by Katrina.[33] Worse disasters than Katrina included the San Francisco earthquake (2000 deaths) and two other hurricanes – the Galveston Texas hurricane in 1900 (6000 deaths) and the Lake Okeechobee hurricane in 1928 (1836 deaths).[34]

Although powerful hurricanes like Katrina are among the worst natural disasters, the annual average number of deaths in the United States from hurricanes is 49, which is lower than the averages for a number of other hazards, including floods, tornadoes, and heat.[35] Lower deaths from hurricanes is not necessarily an indication that hurricanes are less frequent or less severe than these other hazards; rather it may be that deaths from hurricanes have been more successfully prevented through prediction and preparation, than is the case for the other hazards. The average annual monetary damage from hurricanes, over the period 1900-2006 for the United States is about $5 billion, adjusted for inflation and increases in wealth. This is roughly midway between annual average monetary damages from tornadoes and those from floods.[36]

In less developed countries, tropical cyclones are also frequent and severe, but their severity is more likely to have been eclipsed, at least historically, by that of droughts or epidemics. This may be because these countries live at or near a subsistence level in terms of food supply and they have less advanced health care systems. So disasters that affect the food supply or health

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[32] In New Orleans, landfalls for 3, 4, or 5 hurricanes occur every 31, 65, 170 or 1 in 20 years. So 1/31 + 1/65 +1/170 is the probability of a category 3 or 4 or 5 in each year. This sum is .05, implying a 1 in 20 chance each year. Return period data is from http://www.nhc.noaa.gov/HAW2/english/basics/return.shtml.

[33] http://www.ncdc.noaa.gov/oa/reports/tech-report-200501z.pdf.

[34] EM-DAT, The OFDA/CRED International Disaster Database – www.emdat.net – Universite catholique de Louvain – Brussels – Belgium.

[35] http://www.weather.gov/os/hazstats.shtml .

[36] http://www.sip.ucar.edu/sourcebook/hurricanes.jsp.

have a far bigger impact than such disasters would have in developed countries. Nevertheless, in Bangladesh, for example, 8 of the 10 most deadly natural disasters were tropical cyclones. The other most deadly disasters for Bangladesh were a drought in 1943 and an epidemic in 1918. Since these non-cyclone disasters occurred relatively early compared to most of Bangladesh's other worst disasters, it is possible that tropical cyclones may be a greater threat that drought or epidemic in the future, even for a poor country like Bangladesh.

b) **Lead-Time** and **Accuracy**

The ability to forecast hurricanes has been improving. In the United States, forecast track errors for the first part of the current decade were roughly half as large as they were in 1990, and the five day advance forecasts are as accurate as three day forecasts were 15 years ago. Perhaps a more relevant measure of forecast accuracy is the length of coastline subject to a hurricane warning. This is now 510 km versus 730 km a decade earlier. Even so, on average about three-quarters of the coastline under a hurricane warning does not ultimately experience hurricane conditions. Costs of responding to hurricane warnings (evacuation and steps to prevent property damage) are, of course, born throughout the warning area. [37]

c) **Response Costs** and **Loss Reduction**

When a tropical cyclone threatens to make landfall, there are a number of responses that are made. Valuable mobile property, such as boats, ships, aircraft, and land vehicles may be taken out of harm's way. Smaller items with high monetary or sentimental value may be gathered up to be moved. Immovable property, such as houses and other structures, may be secured, e.g. by boarding up windows and securing any loose objects. Most importantly, people in the storm's likely path may be evacuated inland.

The costs of this kind of preparation for a tropical storm landfall vary widely depending on the population density and extent and type of development along the warned coastline. By one estimate, this cost for the United States can be as low as $0.1 million per mile for sparsely settled coastline to in excess of $10 million per mile for metropolitan centers.[38]

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[37] http://www.ametsoc.org/POLICY/2007hurricaneforecasting.html.

[38] http://www.sip.ucar.edu/pdf/01_Hurricane_Forecasting_the_State_of_the_Art.1.pdf.

For a typical 300 mile coastal evacuation zone that exceeds, by a factor of four, the actual length of coast that will ultimately experience hurricane conditions, the “unnecessary” preparation costs incurred would be $22.5 million to $2,250 million. Or course, as long as our forecasts are anything less than perfectly accurate, it is in fact necessary to evacuate a longer stretch of coastline, in order to avoid the hurricane deaths and damages that might otherwise result from imprecision in the forecasted hurricane track. Nevertheless, these numbers, $22.5-$2250 million, provide a rough sense of the cost savings that may be achieved by further improvements in hurricane forecasting accuracy.

Hurricane forecasting in the United States has been very successful, particularly in reducing deaths from hurricanes. At the current state of the art, it is estimated that hurricane forecasts have reduced deaths by 90 percent relative to the forecasting state of the art in 1950.[39] Most deaths now attributed to hurricanes in US result from flooding caused by the heavy rains that accompany hurricanes. Since 1970, hurricane storm surge has not been the primary cause of these deaths, due to the effectiveness of evacuations from storm surge zones.

Property damage from hurricanes has continued to rise over time, despite improvements in forecasting accuracy. This can be attributed to the continuing increase in population and economic development along the coasts of the United States. When the data are adjusted to take account of this secular increase in exposure to hurricane damage, there appears to be no apparent trend in property damage from hurricanes over time.[40] This suggests that the loss reduction in damage to property may simply be a lot more difficult to achieve than the reduction in loss of life that is achievable through evacuations.

d) Early Warning System Cost

It is difficult to estimate the costs of providing hurricane forecasts. No doubt this is partly due to the fact that the hurricane forecasting system relies in part on shared systems, e.g. satellites and radar, that support multiple weather forecasting services in addition to hurricane forecasts. For the United States, the entire National Weather Service budget is a little less than $1 billion. The budget for the National Hurricane Center itself is about $6 million, but this is presumably a gross underestimate of the full costs that might reasonably be allocated to hurricane forecasting in the United States.

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[39] http://www.sip.ucar.edu/pdf/01_Hurricane_Forecasting_the_State_of_the_Art.1.pdf.

[40] http://sciencepolicy.colorado.edu/admin/publication_files/resource-2476-2008.02.pdf.

e) Summary

Early warning systems for tropical cyclones or hurricanes are likely to have high benefits relative to warning systems for most natural disasters. These storms occur frequently and they are sometimes among the most severe of natural disasters. The present ability to predict hurricanes is good and continues to improve over time. While the cost of preparation in response to hurricane warnings is high, the loss reduction from such preparation, especially in terms of saved lives, is also high and has been well demonstrated. These characteristics of tropical cyclones mean that early warning systems for them can create high benefits

2. Tornadoes

A tornado is a column of rapidly rotating air that develops within a thunderstorm. Compared to hurricanes, which can be hundreds of miles wide, tornadoes are much smaller, with a width ranging from less than 100 meters to about a mile. But wind speeds in a tornado are often higher than in hurricanes, sometimes exceeding 250 miles per hour. While hurricanes usually persist for days, tornadoes may appear and disappear in a matter of minutes, and they do so over the land, rather than hundreds of miles out to sea. This means that conditions that might produce tornadoes can be predicted, but tornadoes themselves tend to appear suddenly, and specific warnings cannot be provided before the tornado is already posing an imminent danger.

a) **Frequency** and **Severity**

Tornadoes can occur in many places around the world, but they are most common on the plains to the east of the Rocky Mountains in the United States. Tornadoes occur primarily during the spring and summer seasons. In an average year, there are about 800 tornadoes reported in the United States, making tornado strikes much more numerous than hurricane landfalls.[41] In an average year, the United States has about 54 deaths from tornadoes, which is just slightly above the average number of deaths from hurricanes. The average annual monetary damages from tornadoes in the United States during the period 1950 to 2006 is about $2 billion adjusted for inflation and increases in wealth. This is less than half the average monetary damages from hurricanes. These lower damages from tornadoes suggest that tornadoes may be intrinsically less destructive overall than hurricanes, especially when it is recognized that tornado warnings never come quickly enough for people to take any action that would reduce the property damage from the tornado. Further supporting this observation is the fact that monetary damages from any single tornado are generally much lower than those from any single hurricane. Hurricane Katrina is estimated to have caused $125 billion of monetary damages. The worst recent tornado, Oklahoma City in 1999, is estimated to have caused monetary damages of about $1 billion. Tornadoes, however, partially make up for this relative lack of destructiveness by being far more frequent that hurricanes.[42]

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[41] http://www.nssl.noaa.gov/edu/safety/tornadoguide.html.

[42] http://www.nssl.noaa.gov/users/brooks/public_html/damage/tdam1.html.

b) **Lead-Time** and **Accuracy**

Because tornadoes form suddenly, they cannot be predicted days in advance the way hurricanes can. However, modern weather radar systems have made it possible to detect tornadoes quickly and even to predict the formation of a tornado using observations of wind patterns within a thunderstorm. Overall, these radar systems have increased the average lead-time for tornado warnings from 5 minutes to 13 minutes, and improved the accuracy of warnings from 40 percent to 75 percent.[43]

c) **Response Costs** and **Loss Reduction**

Given the life-threatening risk from tornadoes and the relatively short lead-time between receiving a tornado warning and the arrival of the storm, the only response that makes sense is taking actions that reduce the risk of death or physical injury. These actions have negligible costs, and create large loss reductions. Tornadoes have an unusually simple response calculus and payoff from that response.

d) **Early Warning System Cost**

As with tropical cyclone warning systems, it is difficult to accurately measure the costs of warning systems because many of the components of those systems play roles in multiple functions of the United States National Weather Service.

Dissemination of warnings is always important, and particularly so for tornadoes,because the time to react to a warning is so short. Dissemination of warnings in the United States occurs through a wide variety of channels – directly through NOAA radio, from local television and radio stations, local civil defense sirens, and use of local law enforcement to spread the word about the warning. These systems are most developed in parts of the country that are particularly prone to having dangerous tornadoes. It was reported that the warning dissemination systems in Oklahoma City did a notably good job of communicating the warning

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43 http://celebrating200years.noaa.gov/breakthroughs/tornadowarnings/welcome.html#improved .

prior to the powerful tornado that went through that city in 1999.[44] While the costs of these diverse channels of communication are difficult to estimate, they are not likely to be large in comparison to value of the warnings in saving lives and preventing injuries.

e) Summary

Early warning systems for tornadoes are likely to have benefits that are well in excess of the costs of the warning system, despite the fact that those costs are difficult to precisely estimate. This conclusion is justified by the other features of tornado warning systems which uniformly suggest high benefits -- tornadoes are relatively common natural disasters, responses to tornado warnings are inexpensive, and the loss reduction (i.e. benefit) from appropriate responses to warnings is extremely high value. This loss reduction is lives saved and injuries prevented. In developed countries like the United States, lives are very highly valued, sometimes explicitly, as when public policies involve direct tradeoffs between program costs and reduced risks of mortality or morbidity.[45]

In less developed countries, it would be necessary to consider a tornado warning system in relation to competing uses for public funds to improve nutrition, immunization, or other programs that also save lives. It may be true that such other uses have higher value in terms of lives saved than a tornado warning system. On the other hand, all of these programs that save lives may be under-funded relative to some other uses to which public funds are being committed.

[44] http://www.usatoday.com/weather/tornado/storms/1999/w503tora.htm .

[45] http://yosemite.epa.gov/ee/epa/eermfile.nsf/vwAN/EE-0483-01.pdf/$File/EE-0483-01.pdf.

3. Floods

Floods can be caused by snow melt, ice jams on rivers, breaking of dams or levees, storm surge and/or torrential rain caused by hurricanes, or simply as a result of heavy rain. Even though deaths from hurricane-related flooding are counted as hurricane deaths rather than flood deaths, floods, particularly flash floods, are among the most deadly of natural disasters in the United States. Floods are also serious natural disasters in less developed countries such as India and Bangladesh where annual monsoons often cause result in loss of life as well as extensive damage to property and crops.

a) **Frequency** and **Severity**

In the United States, flooding is the most common of natural disasters, according to NOAA.[46] Floods are also among the most deadly of natural disasters in the United States. In the thirty years from 1977 to 2006, deaths in the United States from floods averaged 99 per year, as compared to 54 per year for tornadoes, and 49 per year for hurricanes. Only heat waves appear to have high average annual deaths.

Floods are also common and deadly in less developed countries. In China, for example, four of the ten worst natural disasters between 1900 and 2008 were floods. Moreover, the loss of life from these four floods was more than half of the combined loss of life from all of the ten worst natural disasters.[47]

In the United States, most of the flood related deaths are caused by flash floods. In 2006, the most recent year for which data are available, flash floods claimed 59 lives, compared to 17 for river floods.[48] In 1997, which had extensive snowmelt flooding in MN and ND, flash floods claimed 86 lives, compared to 32 lost in other floods.[49]

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[46] http://www.nssl.noaa.gov/primer/flood/fld_damage.html .

[47] http://www.emdat.be/Database/CountryProfile/countryprofile2.php#top10lists .

[48] http://www.nws.noaa.gov/om/hazstats/sum06.pdf.

[49] http://www.nws.noaa.gov/om/hazstats/sum97.pdf .

Average annual damages from floods in the United States between 1955 and 2006 were about $7 billion dollars, adjusted for inflation and wealth increases.[50] This is equal to the total of average annual damages for hurricanes and tornadoes combined.

b) **Lead-Time** and **Accuracy**

The problem of forecasting floods is quite different depending on the nature of the flood. Floods that result from excessive snowmelt may be predicted weeks in advance based on measured snow on the ground. On the other hand, floods from breeched dams or levees are likely to be unpredictable until the actual breech occurs; after that, flooding downstream of the breech can be predicted, but not with a great deal of lead-time.

Flash floods resulting from heavy rainfall are perhaps the most difficult to predict. The Unites States National Weather Service defines flash floods as floods that occur within six hours of a causative event, such as sudden heavy rain. Whether a flash flood occurs depends not only on the amount of rainfall received in a given area over a given period of time, but also on hydrologic conditions such as topography, soil moisture, and degree of urbanization in the affected area.[51]

NOAA data indicate that the accuracy of their flash flood warnings is 89 percent, with an average lead-time of 49 minutes.[52] This means that flash flood warnings in the United States are highly accurate. Lead-time, though considerably better than the 13 minutes for tornadoes, is still short enough that response must be focused on saving lives rather than protecting property.

c) **Response Costs** and **Loss Reduction**

If flood warnings are issued several hours or even a few days before a flood is likely to occur, then it may be possible to prepare one's home or other buildings to better survive the flood. Small important items, such as records or keepsakes can be collected to be taken out of the

[50] http://www.sip.ucar.edu/sourcebook/floods.jsp.

[51] http://www.srh.noaa.gov/alr/papers/content/seFlashFlood.pdf .

[52] www.nws.noaa.gov/com/files/All_GPRA2006.ppt .

home, while other larger items of importance or value can be moved to a higher floor. In addition, electrical power and gas lines can be shut off. If there are days of advance warning, setting up sandbag levees to protect structures sometimes may be possible. Most of these steps are not particularly expensive, with the possible exception of sandbagging.

If there is a flash flood warning, then it is advisable to move to higher ground without delay. As mentioned above, flash flood warnings are quite accurate and they are issued with an average lead-time of 49 minutes. Given that safe high ground is rarely far away, and that the number of people needing to evacuate is small, at least relative to those needing to evacuate an incoming hurricane, the costs of evacuation for a flash flood are minor.

Given the accuracy and lead-time of flash flood warnings in the United States, it is a little surprising that the death toll from flash flood is as high as it is. It appears that fatalities from flash floods are as high as they are largely because people do not really appreciate the seriousness of the risk from floods, and in particular they do not understand the risks they take when they drive motor vehicles over flooded roadways. Over half of the deaths from floods occur when motor vehicles in a foot or two of water begin to float and then are swept away by the current. Most of these deaths could be prevented if people understood the true risk of driving a vehicle on a flooded roadway and behaved more cautiously. A major education effort is underway to improve public understanding of this risk.[53]

With respect to the monetary damages from flooding, it does not seem likely that the loss reduction from preparations is very large. There are two reasons for this. First, the majority of flooding incidents are flash floods, with relatively short lead-times that offer no real opportunity to protect physical property. Second, even when the flooding incident is one for which a longer warning lead-time is provided, most of the actions that can be taken to protect property (e.g. removing some small items, and moving larger ones to a higher floor) do not seem to offer a very large potential for reducing the losses from flooding.

With respect to the loss of life, it does seem likely that flood warnings do create a substantial loss reduction. With lead-times of 49 minutes for flash floods and more for other floods, there would seem to be ample time to take steps that save lives. And, as mentioned above, the potential saving of lives may be greater than what has been realized to date, because people still seem to be taking unnecessary risks in driving over flooded roadways.

d) Early Warning System Cost

[53] http://www.nws.noaa.gov/floodsafety/tadd.shtml .

Once again, the costs of flood warning systems in the United States are substantially shared costs within the National Weather Service. This makes it difficult to estimate what cost should be allocated to flood warning.

e) Summary

Floods are a very common type of natural disaster, and they cause substantial amounts of property damage, and substantial losses of life. While there seems to be limited potential for a flood warning system to produce significant benefits with respect to property damage from floods, the large numbers of lives that are being saved by flood warning systems is quite likely large, and could be larger with further education of the public. Moreover, these lives are saved by the simple and inexpensive step of evacuating people in flood threatened areas to safe high ground. This makes it highly likely that the benefits of an early warning system for floods would substantially exceed costs of such a system, and certainly so in regions of the world where a high value is attributed to saving lives.

4. Heat Waves

"Heat waves" are a relatively underappreciated natural disaster. A "heat wave" may be defined as a period of time when temperature and humidity conditions change relatively quickly in ways that present a risk to human health. Heat waves never causes property damage, and they may create only minor discomfort for healthy and relatively well-to-do people who live, work, and drive in air-conditioned spaces. But to people living in non-air-conditioned spaces, especially if they are elderly or unhealthy, a heat wave is a life-threatening event. Surprising to many, heat waves actually top the list of weather related causes of death in the United States, with 170 deaths annually.[54]

The research on the effects of heat on mortality has typically focused on urban populations in developed countries. It is speculated that the effect of heat on populations in less developed countries may also be significant because people in these countries may have even less access to air conditioned spaces than poor urban populations in the developed countries. But there is no research to support this speculation.[55]

Heat waves are most dangerous to people who are unhealthy, and to the elderly, whose bodies do not adapt as well to heat and who are less able to recognize the effects of heat and dehydration and to respond appropriately. Also, to the extent that people in these at-risk groups live alone, they are at greater risk of dying before anyone knows that a problem is developing and can seek medical help.

a) **Frequency** and **Severity**

Periods when the risk of death from heat is elevated ("heat waves") are very common. In one study that focused on heat waves in Philadelphia during the four years 1995-1998, there were 52 periods of one or more days in which heat posed a risk of elevated mortality.[56]

The United States National Weather Service identifies heat as the most dangerous natural hazard, with an average of 170 fatalities per year for the ten year period from 1997 to 2006 (heat related data have not been kept as long as data for other hazards). By comparison, the next most dangerous natural hazard is hurricanes with an average of 117 fatalities per year during these years (which do include Hurricane Katrina in 2005).[57]

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[54] http://www.weather.gov/os/hazstats.shtml .

[55] http://www.ipcc.ch/ipccreports/tar/wg2/353.htm .

[56] http://ams.allenpress.com/archive/1520-0477/85/8/pdf/i1520-0477-85-8-1067.pdf.

[57] http://www.weather.gov/os/hazstats.shtml .

Heat waves are unusual among natural hazards in that they do not create property damage. However, heat waves often are associated with drought, and drought is a natural disaster that primarily causes proper damage in the form of loss of crops and livestock. Drought is discussed separately below.

b) Lead-Time and **Accuracy**

Heat wave forecasts represent only a modest extension of everyday weather forecasts produced by the United States National Weather Service (NWS). The NWS calculates a Heat Index that summarizes the combined effects of heat and humidity, and which provides an indicator of health risk from heat. Other more sophisticated measures of the health risk for weather conditions have also been developed.[58]

The accuracy of forecasts has been evaluated for a heat wave warning system implemented in Rome, Italy. This evaluation found that 86 percent of the alarms were correctly issued, implying that there were false alarms only 14 percent of the time. On the other hand, and not surprisingly, the Rome system tending to be conservative about calling alarms, so that there were relatively many situations where an alarm should have been called but was not.[59]

These results highlight the fact that one usually has to make a tradeoff between calling alarms when one should not (i.e. false alarms), and calling alarms when one should. Finding the right balance here involves consideration of the costs of responding to false alarms and the costs of failing to call an alarm when one should. Since the cost of failing to call an alarm when one should is measured in lives lost, one might think the system should be tuned to err on the side of over-predicting dangerous heat situations. However, if there are too many false alarms, this may decrease public response to warnings, leading to loss of life because of this reduced response. So finding the right balance involves making what may be a delicate assessment of the likely public reaction to false alarms.

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[58] http://www.bmj.com/cgi/content/full/321/7262/650.
[59] http://www.euro.who.int/document/e82629.pdf p.52.

c) **Response Costs** and **Loss Reduction**

The costs of responding to a warning of a heat wave appear to be very modest. When a heat wave threatens a vulnerable population, a number of simple actions appear to be effective in reducing loss of life caused by the heat wave. The study of the heat wave warning system in Philadelphia indicated that responses to a warning included actions such as these: radio and television announcements warning of the danger and informing of appropriate steps to reduce the risk, encouragement of "buddy systems" to check on vulnerable neighbors, staffing a "heat-line" to field questions, extending operating hours for air-conditioned senior centers, adding shifts for emergency medical teams. Many of these actions have no direct cost (relative to the costs that would have existed without a heat wave warning). The actions that do have direct costs, such as wages for extended hours for "heat-line" and emergency medical staff, appear to have been less than $10,000 per day, or a total of $210,000 for all the days in Philadelphia study in which a warning was in effect. These are small numbers.[60]

The loss reduction from a heat wave warning is the value of lives saved. In a developed country like the United States, the monetary value that is assigned to human lives is very high.[61] The Philadelphia heat wave study estimated that the warning system there saved 117 lives over the four years of the study, creating a benefit (i.e. loss reduction) of nearly $500 million.

d) Early Warning System Cost

The cost of an early warning system for heat waves is difficult to separate from the other costs of a weather forecast system. It seems likely, however, that the incremental cost of producing heat wave warnings, given a functioning weather forecasting system, would be almost negligible.

e) Summary

The reasons to think a heat wave warning system has large net benefits are compelling. Heat waves are a common occurrence in geographic regions that are susceptible to life-threatening heat waves. Although heat waves pose no threat to property, they are the leading cause of mortality among various weather-related natural disasters. The incremental costs of forecasting a heat wave are small; and the cost of responding to forecasted heat waves is small. On the other hand, the saving of lives that appears possible from a warnings system is large.

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[60] http://ams.allenpress.com/archive/1520-0477/85/8/pdf/i1520-0477-85-8-1067.pdf .

[61] http://yosemite.epa.gov/ee/epa/eermfile.nsf/vwAN/EE-0483-01.pdf/$File/EE-0483-01.pdf .

While there is reason to believe that lives are not valued as highly in LDCs as in the developed world, it nevertheless seems likely that a heat wave warning system in LDCs would have significant positive net benefits if there is already a functioning weather forecasting system in the LDC.

5. Droughts

Droughts are different from other natural disasters in several respects. In the developed world they rarely claim lives, since wealthy countries have the financial ability to replace food production lost due to droughts. In years past, they have been among the most deadly of hazards in less developed countries, though this may be less true now and into the future as LDC's have become wealthier and international aid responses have developed and become more effective. In terms of property damage, however, droughts are among the most costly of natural hazards. In addition, they are difficult to predict, since they are inherently long-term weather events lasting months or years, and predicting weather over these kinds of time spans is harder than predicting weather over the next few to several days.

a) **Frequency** and **Severity**

Droughts are very common and very costly. By one estimate, droughts have affected more people in the United States than any other natural hazard, and the costs of drought in the United States average $6-8 billion per year. [62] The most recent United States drought, in the late 1980's, is believed to be the most costly natural disaster ever for that country, with cost estimated at $39 billion.[63]

Costs in less developed countries often include serious loss of life. As recently as 2002, there was a drought in India that is estimated to have caused 300,000 deaths. While this is an enormous loss of life, there were several droughts earlier in the twentieth century that claimed from 1 to 3 million lives each.[64]

b) **Lead-Time** and **Accuracy**

Predicting droughts is difficult. Some progress has been made in predicting droughts that are associated with the El Nino and the Southern Oscillation (ENSO). ENSO phases that may cause droughts in some parts of the United States can now be predicted reasonably well several

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[62] http://www.ncdc.noaa.gov/paleo/drought/drght_alleve.html .

[63] http://www.ncdc.noaa.gov/paleo/drought/drght_history.html .

[64] http://www.emdat.be/Database/DisasterProfile/profile_disasters.php?disgroup=natural&period=1900%242008&dis_type=Drought&Submit=Display+Disaster+Profile#top10lists .

months in advance of the actual event. The ability to predict rain and droughts associated with ENSO is also perhaps even more important for countries such as Peru that are more affected by ENSO and whose economies are generally more sensitive to the weather.[65] On the other hand, for countries in Asia, Africa and Europe, ENSO predictions are not useful for predicting droughts.

Even for regions where ENSO predictions are helpful in predicting droughts, the ability to predict droughts lasting for several years remains elusive. The two worst droughts in the United States during the twentieth century were the Dust Bowl drought of the 1930's and a drought in the 1950's. Both covered large parts of the middle of the country. We do not really understand what caused these droughts, let alone have the ability to predict future droughts of this magnitude.[66]

c) **Response Costs** and **Loss Reduction**

For droughts there are two types of actions that can be taken to respond to the threat of droughts. One type of action is to reduce dependence on natural rainfall. This can be done by investing in irrigation systems that use water from wells or surface reservoirs. This is a type of action that would not be taken in response to warnings, per se, and the damage reduction it creates could not be counted as a benefit of an early warning system. It should also be noted that actions such as these are often not sustainable, as when the draw on underground aquifers exhausts those aquifers; also, these kinds of actions may have negative spillovers for other people, as when damming of a river for irrigation seriously reduces the water previously available to people living downstream on the river.

Other actions that may be taken in response to a drought forecast include true responses to forecasts that create benefits from the existence of the forecast system. For example, the management of water reservoirs can take a forecast of drought into its decisions by taking steps that conserve water now in order to have more water later when the drought occurs.

Another example of actions that may be taken in response to drought forecasts involves shifting the type of crops that are grown from those that need plentiful rainfall to those that are more tolerant of limited rainfall. This kind of response is actively managed as a matter of public policy in Peru.[67]

[65] http://www.pmel.noaa.gov/tao/elnino/impacts.html .
[66] http://www.ncdc.noaa.gov/paleo/drought/drght_alleve.html .

[67] http://www.pmel.noaa.gov/tao/elnino/impacts.html#part2 .

In the United States, there is no centralized system for planning crop planting decisions in light of ENSO predictions. However, it is expected that farmers would respond to ENSO forecasts by modifying their planting decisions appropriately. One study estimated that the benefits of such responses in the United States would average about $250 million per year.[68]

Another example of actions that may be taken in response to droughts forecasts involves management of food reserves. Food reserves are held, at some cost, because future crop production is uncertain. If a forecast makes future crop production more certain, food reserves can be decreased or increased as appropriate. This increased efficiency in the use of food reserves as a buffer against food production uncertainty has been estimated to have a value for the United States of $240 million per year for a perfect ENSO forecast, for a single crop, corn.[69]

The above studies go beyond simple estimation of response costs and loss reductions to integrate these concepts together with the other drivers of warning system value (frequency, severity, lead-time, accuracy) to arrive at an overall value of a forecast system for ENSO. Each study, however, is focused on a single element of the overall set of systems that could be expected to produce benefits from an ENSO forecast. Also, it should be remembered that forecasting ENSO is only a small piece of the problem of forecasting droughts. If we were better able to forecast droughts more generally, the total loss reductions likely would be orders of magnitude higher than the numbers mentioned above.

d) Early Warning System Cost

It is difficult to estimate cost of an early warning system for droughts, since at this point we do not really know how to make such forecasts.

e) Summary

It is likely that the benefits of an early warning system for drought would be very high, given that droughts are both common and create large damages, both of a monetary nature, and in LDC's in terms of loss of life. However, our ability to predict droughts is quite limited at this point in time, and this makes speculation about the value of a warning system for drought somewhat moot. Until we develop a better capacity to forecast drought, the chief response to the threat of drought will be an appropriate set of policies to protect against the impacts of drought, given the (prior) probabilities of drought occurring in any given region of the world. This response might involve research to better understand those probabilities, improvements in food storage systems and management, improvements in cultivation methods and crop choices,

[68] http://ioc.unesco.org/goos/el_nino.pdf -- pp. 29-39.

[69] http://ioc.unesco.org/goos/el_nino.pdf --- pp. 41-42.

and improvements in irrigation, with particular attention to management policies for ground water and above ground reservoirs.

B. Geologic Hazards

1. Earthquakes

Earthquakes are movements of the ground that are believed to occur as a result of the earth's tectonic plates suddenly sliding with respect to each other. Because of this, earthquakes are more common in regions of the world where these plates meet, such as the Pacific Ring of Fire, a semicircular strip of land extending up the west coast of North America, and down the east coast of Asia. This is an area in which volcanoes and earthquakes are more common. Volcanoes, like earthquakes, are believed to commonly occur where tectonic plates meet. Earthquakes can cause property damage, deaths, and injuries. Deaths and injuries result when structures collapse on people, or when the earthquake creates a Tsunami, a natural hazard that is discussed separately below.

a) **Frequency** and **Severity**

Earthquakes in general are extremely common, though damaging earthquakes are uncommon relative to floods or tornadoes, for example. Worldwide, it is estimated that there are 500,000 detectable earthquakes annually; however, only 100 of these earthquakes cause damage in a typical year.[70]

Major earthquakes are among the most serious of natural hazards. The costs of earthquakes are different depending on whether the affected country is a developed country or a less developed country. The 1995 earthquake that affected Japan, for example caused about 5000 deaths, but the property damage was a staggering $100 billion. In contrast, the May 2008 earthquake in China caused 87,000 deaths, but only $20 billion of property damage.[71]

[70] http://earthquake.usgs.gov/learning/facts.php .

[71] http://www.emdat.be/Database/DisasterProfile/profile_disasters.php?disgroup=natural&dis_type=Earthquake%20(seismic%20activity)&period=1989$2008#top10lists .

b) **Lead-Time** and **Accuracy**

One can predict with certainty that an earthquake will occur every day, somewhere on the globe, but one cannot predict where one will occur or how strong it will be.[72] The truth is that we are unable to make useful predictions of earthquakes. In some cases it is possible to develop a rough estimate of the years between recurrences of earthquakes on a particular fault line, but an earthquake due every 100 years, say, could easily arrive in 50 years or 150 years, without this being particularly unusual. In the 1980's, the United States Geological Survey and the State of California prepared to carefully monitor a site that had seen several recent earthquakes separated by 20-25 years, the last one having been in 1966. However, the anticipated earthquake did not arrive until 2004. This kind of prediction accuracy is simply insufficient to support an early warning system.[73]

Japan and Mexico have implemented systems that sense very small tremors that might be the leading edge of a serious earthquake. However, the lead-time of warnings produced this way may be insufficient to do any response except signal automatic devices to take some predetermined action. For example, there are self-contained devices that can be hooked up to gas lines that sense minute tremors and shut off the gas to a house before possible major shaking starts.[74]

c) **Response Costs** and **Loss Reduction**

For the most part, the only responses to earthquake hazards are to make systems less vulnerable to the destructive force of an earthquake, which will certainly come, but the arrival time of which cannot be predicted with any accuracy. Such responses would include designing and building structures, roads, dams, and bridges that are able to withstand an anticipated earthquake. Such responses are not likely to be particularly expensive for new construction, but are likely to be more expensive for retrofits. One study of retrofitting schools in Turkey found that the costs exceed the benefits, considering only property damage from an earthquake, but that if lives would be saved by the retrofitting, then the benefits exceed the costs.[75]

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[72] **http://earthquake.usgs.gov/learning/topics/100_chance.php .**

[73] http://www.usgs.gov/corecast/details.asp?ID=76 .

[74] http://www.usgs.gov/corecast/details.asp?ID=76 .

[75] http://info.worldbank.org/etools/docs/library/152948/SmythKunreuther_EarthquakeCostBenefit.pdf .

d) Early Warning System Cost

Because it is not now possible to forecast earthquakes, an early warning system for earthquakes is not feasible.

e) Summary

Earthquakes are common and destructive natural disasters. Since it is not possible to forecast earthquakes, an early warning system for earthquakes is not possible. However, it likely makes a great deal of sense, in areas prone to earthquakes, to design new construction of buildings, roads, dams, bridges, etc. to withstand earthquakes. In some cases, it may also make sense to retrofit structures to withstand earthquakes, particularly if the number of lives potentially saved by such retrofitting is large.

2. Tsunamis

Tsunamis are huge ocean waves, potentially exceeding 30 meters in height when they reach land. They are most often generated by earthquakes, though not all earthquakes create tsunamis. On December 26, 2004, a magnitude 9 earthquake off the Sumatra coast generated a tsunami that may have claimed as many as 250,000 lives and caused damages of $10 billion. Although the start of a tsunami is no more predictable than the earthquake that generates it, tsunamis take time to travel over oceans, making it possible to warn many people living on affected coasts.

a) **Frequency** and **Severity**

Major tsunamis are relatively uncommon, occurring about once each decade on average. The majority of tsunamis (59%) occur in the Pacific Ocean; tsunamis are less common in the Mediterranean (25%), the Atlantic (12%), and the Indian (4%) oceans.[76] Given the really low frequency of tsunamis in the Indian Ocean, it is somewhat more understandable that there was a failure to respond appropriately in that region, either in creating a warning system in the first place or in taking appropriate action in response to the knowledge that a magnitude 9 earthquake had occurred. Indeed, even earthquake experts considered the 2004 Indian Ocean tsunami a real surprise.[77]

Since 1900, there have been 13 tsunamis worldwide that killed 100 or more people. Excluding the devastating 2004 tsunami in the Indian Ocean that may have killed up to 250,000 people, the next most deadly tsunami since 1900 was one in Japan in 1933 that killed 3022. In terms of property damage, the 2004 tsunami is estimated to have caused damages of $10 billion. The next most costly tsunami in terms of property damage was one in Japan in 1993 that causes $1.2 billion in property damage (and 230 deaths).[78]

b) **Lead-Time** and **Accuracy**

Tsunami warning systems are based on detection of earthquakes, and assessment of their potential to produce a tsunami. To produce a tsunami, earthquakes need to have their hypocenter under the ocean and not too deep underground. When an earthquake meets these criteria, a warning will be issued. Japan, with one of the most advanced warning systems, is able to get a warning out in as few as three minutes after the initiating earthquake has occurred.[79]

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[76] http://www.prh.noaa.gov/ptwc/faq.php#8 .

[77] http://www.voanews.com/english/archive/2005-02/2005-02-08-voa28.cfm.

[78] http://www.prh.noaa.gov/ptwc/faq.php#8.

[79] http://www.voanews.com/english/archive/2005-02/2005-02-08-voa28.cfm .

For coastlines that are very close to the hypocenter of the earthquake, a three minute warning still may not be enough time to accomplish any significant evacuation. But for more distant coastlines, three minutes is more than adequate, as a tsunami can take many hours to reach a distant coastline.

It is interesting to note that there have been instances, including the 2004 Indian Ocean tsunami, where people, having felt the earthquake and understanding the risk of tsunami, sought safety of their own accord, and did not perish as a result. In the case of the 2004 Indian Ocean tsunami, the people who survived this way were primitive people, who lived in closer association with the land than more technologically advanced people.[80] However, it is not just primitive people who have saved themselves in this way. The 1993 tsunami that killed 230 was generated by an earthquake very close to Japan, making it impossible for warnings (issued within 10 minutes, at that time) to make a difference. Nevertheless, the death toll was reduced because people had experience with earthquakes and tsunamis, and they understood that it was a sensible precaution to move away from the coast when an earthquake is felt.[81]

The tsunami warning system that has been operating in the Pacific Ocean since 1965 has been characterized by a high false alarm rate, estimated at 75 percent.[82] For the rare earthquake that is magnitude 9 or so, a tsunami is almost certain to result. However, for lesser earthquakes, a tsunami may or may not result. Warnings can be issued based on seismometer readings indicating an earthquake has occurred, but confirming the existence of a tsunami requires a system to quickly measure and report the existence of an actual wave in the ocean. Recently, a system known as DART has been deployed. This system uses ocean floor pressure sensors and a buoy to detect a tsunami wave, and transmit it's readings via communications satellite. This system holds promise to reduce the percentage of false alarms significantly.[83] The DART system is in use in the Pacific, and also is being used to some extent in the new Indian Ocean tsunami warning system.[84]

c) **Response Costs** and **Loss Reduction**

For the most part, the appropriate response to tsunami warnings is evacuation of people from threatened coastlines; typically, there is not time to protect property. Evacuations are

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[80] http://www.voanews.com/english/archive/2005-02/2005-02-08-voa28.cfm .
[81] http://www.drgeorgepc.com/Tsunami1993JAPANOkushiri.html .
[82] http://www.wired.com/science/discoveries/news/2005/02/66586 .
[83] http://www.magazine.noaa.gov/stories/mag153.htm .
[84] http://news.bbc.co.uk/2/hi/science/nature/4524642.stm .

expensive – it is estimated that an evacuation in Hawaii costs $68 million in lost business and productivity.[85]

The loss reduction would depend on the number of lives that an early warning would save. The 2004 Indian Ocean tsunami was a rather extreme case, but with something like 250,000 lives lost, if even a small fraction of these deaths were prevented, the loss reduction would be huge.

d) Early Warning System Cost

The Indian Ocean tsunami warning system is expected to cost $200 million. Although the annual cost of running the Pacific Ocean warning system is $2 million, the Indian Ocean system is expected to cost $25 million per year, apparently because most of the countries in the region are planning on having their own local organization to oversee at least parts of the warning system.[86] If these numbers are correct, it pretty strongly suggests that there would be big economies in setting up a collective system for the Indian Ocean.

It is also apparent that a public education campaign is a necessary part of any successful early warning system for tsunamis; indeed, it has been argued that better public awareness alone might have saved a large number of lives that were lost in the 2004 tsunami.[87] The knowledge that a magnitude 9 earthquake had occurred off Sumatra existed, even though there was no system to confirm the existence of a wave. However, had there been more understanding of the high likelihood of a tsunami, given the size of that earthquake, officials could reasonably have chosen to initiate evacuations.

Besides public education, it will also be necessary to install warning systems, such as sirens, and prepare the general population and officials to handle large scale evacuations if a tsunami is forecast. This will require a significant effort and expense for the countries surrounding the Indian Ocean.[88]

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[85] http://www.magazine.noaa.gov/stories/mag153.htm .

[86] http://www.usc.edu/dept/tsunamis/2005/news/articles/pdfs/NDM_Indian_Ocean_Tsunami_Warning_System.pdf .

[87] http://www.usc.edu/dept/tsunamis/2005/news/articles/pdfs/NDM_Indian_Ocean_Tsunami_Warning_System.pdf.

[88] http://www.voanews.com/english/archive/2005-02/2005-02-08-voa28.cfm .

e) Summary

Major tsunamis are infrequent. And warning systems in the past have been plagued with false alarms. This means that that there are relatively few opportunities for a warning system to produce benefits, and a significant risk that when a valid warning is issued, it will not be given the attention it should be given if it is to save a large number of lives. Nevertheless, the potential savings of life are very high, and this may justify an early warning system despite the above issues. Modern technologies hold significant promise for reducing the false alarm rate, and this may be very important if a warning system is to be effective; it is likely worth the extra cost to have these technologies as part of a warning system. Finally, countries and localities will need to make a serious and sustained effort to prepare for evacuations, if a tsunami warning system is to realize the benefits it promises.

3. Volcanic eruptions

Volcanic eruptions are less common than many other kinds of natural hazards. However, they can sometimes cause large losses of life and property. They do this in a variety of ways, including pyroclastic flows (superheated flows of air, ash, and gases that can kill instantly), to ash fallout that can cause roofs to collapse and ruin crops, to lahars (floods of mud/water/volcanic debris) that are extremely deadly and destructive. Our ability to predict eruptions appears to have improved considerably in recent decades and to be quite good at this time.

a) **Frequency** and **Severity**

Worldwide, there are 50-70 volcanic eruptions per year, but only 2-4 of these cause serious injuries or deaths.[89] Part of the reason that few volcanic eruptions have significant impacts is that a large proportion of eruptions are essentially part of ongoing volcanic activity at known locations such as Mt. Kilauea in Hawaii. But it is also true that volcanic eruptions are simply less common than many other natural hazards.

In terms of loss of life, the most destructive volcano in the last 100 years was the 1985 eruption of Nevado del Ruiz in Columbia. This volcano is believed to have killed about 22,000 people and caused $1 billion of damage.[90] The eruption of Mt. St. Helens in the United States in 1980 was the second worst in 100 years in terms of property damage, estimated at $860 million. The number of lives lost in the Mt. St. Helens eruption was a relatively low 57, though it is estimated that as many as 20,000 could have been lost if warnings had not been made and evacuations undertaken prior to the actual eruption.[91]

In 1991, Mt. Pinatubo in the Philippines erupted. This was the third most costly eruption in the last 100 years, but because warnings were given and evacuations undertaken, the number of lives lost was a relatively modest 300. Most of these deaths occurred from roofs collapsing under the weight of volcanic ash, spread widely by winds from Typhoon Yunya, and made heavy by being saturated with rain from the typhoon.[92]

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[89] http://www.geotimes.org/nov07/article.html?id=feature_danger.html .

[90] http://www.emdat.be/Database/DisasterProfile/profile_disasters.php?disgroup=natural&period=1900%242008&dis_type=Volcano&Submit=Display+Disaster+Profile#top10lists .

[91] http://www.pbs.org/wgbh/nova/vesuvius/predict.html .

[92] http://vulcan.wr.usgs.gov/Volcanoes/Philippines/Pinatubo/description_pinatubo.html .

b) Lead-Time and **Accuracy**

The Mt. Pinatubo eruption of 1991 was preceded almost a year earlier by a magnitude 7.8 earthquake 100 km from the Pinatubo volcano. This earthquake was believed to be indicative of activity in the volcano. Then, three or four months before the eruption, a number of small earthquakes were felt and there were small explosions in vents that dusted some nearby villages with ash. Around this time, volcanologists began to study the mountain, and the first small evacuation of 5000 people occurred. Broader warnings were issued on June 5 and June 9, leading to the evacuation of 25000 people. On June 10, Clark Air Base was evacuated, removing an additional 18,000 people from danger. On June 12, the danger radius was extended to 30 km, resulting in a total evacuation of 58,000 people. On June 15, the actual eruption occurred.[93]

Like the Pinatubo eruption, the Nevado del Ruiz eruption was also preceded by many earthquakes starting almost a year before the ultimate deadly eruption. However, there were two differences that contributed to the far worse consequences of the Nevado del Ruiz eruption. One was that Columbia had no indigenous ability to monitor volcanic activity, and instead relied on haphazard help from other countries and the United Nations. Second, and perhaps more importantly, local officials were reluctant to accept the evacuation recommendations they were given.[94] Hindsight is 20/20, but it does appear that the Nevado del Ruiz eruption could have been much less deadly than it was, if better decisions had been made both about monitoring the volcano prior to its eruption and about ordering evacuations when the threat justified doing so.

In 1976, the Suffriere volcano on the French island of Guadeloupe exhibited seismic activity that suggested an eruption would happen soon. There was considerable scientific disagreement at the time over whether an evacuation was appropriate, but the decision was made to evacuate. As it turned out, the volcano did erupt, but not in a way that would have caused loss of life. This is often cited as an example of a false alarm, though there are those who argue that it was the right decision at the time, given the information available at the time. It may also be true that scientists' ability to predict volcanic eruptions was significantly less developed in 1976 than it is now.[95]

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[93] http://geography.about.com/od/globalproblemsandissues/a/pinatubo.htm .

[94] http://www.geology.sdsu.edu/how_volcanoes_work/Nevado.html and http://www.timeshighereducation.co.uk/story.asp?storyCode=145874&sectioncode=26 .

[95] http://www.cite-sciences.fr/francais/ala_cite/science_actualites/sitesactu/question_actu.php?id_article=81&langue=an .

Mt. Rainier in Washington state is a volcano that last erupted in the 19th century. Geologic evidence indicates that some past eruptions there have produced lahars that have extended down into the surrounding lowlands; about 150,000 people now live on top of deposits from past lahars. Mt. Rainier is actively watched for signs of possible future eruptions, and in addition, a system of acoustic flow monitors is in place to detect ground vibrations of a lahar. This system would provide about 40 minutes warning for the first densely populated area that would be hit by a lahar.[96]

Overall, it appears that volcanic eruptions are somewhat idiosyncratic, and that forecasting eruptions and their likely consequences must be done on a case-by-case basis. For example, the unique history of each volcano provides clues about the possible cycle time between eruptions for that volcano, and, that history can suggest the type of eruption that may occur in the future. Mt. Kilauea, for example, tends to produce nicely behaved, slow moving lava flows. Mt. St. Helens, on the other hand, produced an explosive eruption that is characteristic of volcanoes in the Cascade Mountains. What made Nevado del Ruiz so deadly in 1985 (as well as previously in 1845 and 1595) was the lahar that it created. That lahar was created when a relatively small magna ejection melted the surrounding glacier and started a flood/landslide of glacial debris that moved swiftly and forcefully down the mountainside, destroying almost everything in its path.

c) **Response Costs** and **Loss Reduction**

Evacuations are expensive, since the population's normal ways of making a livelihood are suspended, and additional costs must be born to take care of people in the locations to which they have been evacuated. Costs and logistical problems of evacuations in advance of volcanic eruptions may be higher than those for hurricanes, due to the fact that such eruptions occur rarely, and affected local authorities and populations are not experienced in the process of evacuation. Also, though the timing of warnings and evacuations seems to have been impressively accurate for the Mt. Pinatubo eruption, it is likely that evacuations for a threatened volcanic eruption may need to be taken further in advance of the actual eruption than is the case for hurricanes, because the precise timing of an eruption is harder to pinpoint than the precise timing of a hurricane landfall. Evacuations which are earlier, on average, relative to the uncertain hazard will be more expensive.

It has been observed that when a country faces a possible disaster, such as a volcanic eruption, the country may have incentives that inappropriately affect its decision about whether to order an evacuation. If an evacuation is ordered, the costs of that evacuation will be born

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[96] http://www.piercecountywa.org/xml/abtus/ourorg/dem/Mt%20rainier%20learning%20to%20live%20w%20risk.pdf .

solely by the country; but if the evacuation is not ordered and a disaster results, the country can expect massive international relief efforts. On the other hand, it is also true, at least in countries with a free press, that if scientists warn of a disaster and that warning is ignored by political authorities and then disaster strikes, this can create unwanted negative publicity for those authorities. So the disincentive to evacuate may not be a significant issue, except in countries with a controlled press. [97]

The disincentive to evacuate because there is an expectation of international relief if a disaster strikes is similar to the disincentive to evacuate because local authorities receive favorable publicity from press coverage of relief efforts after a disaster occurs, but receive relatively little public recognition of an evacuation that saves lives, and potentially very negative publicity, if an evacuation is ordered and turns out to have been unnecessary.

d) Early Warning System Cost

Systems to forecast volcanic eruptions are a little different from systems to predict weather hazards, such as hurricane strikes. Much of the infrastructure to predict hurricanes also serves the purpose of providing routine weather forecasts, something that would likely be done anyway, even if there were never any hurricane to be concerned about. For volcanoes, some of the infrastructure for eruption forecasting would have a shared use in monitoring earthquake activity, but much of it would appear to be specific to the isolated activity of predicting eruptions. Moreover, because eruption events are relatively rare, the costs of maintaining a capacity to predict them would be spread over relatively few events. These are reasons why one might expect the costs of an early warning system for volcanic eruptions to be somewhat higher than those for weather events, on a "per-life-saved" basis.

In view of the above, there may be a case for collective action among countries to support a single or a few regional organizations to forecast volcanic eruptions. Then when earthquake activity suggests a possible eruption, a team of scientists could be sent to the volcano to provide the necessary monitoring and prediction. While this may make economic sense, it is easy to imagine political difficulties in actually implementing such an idea.

If the "standing offer" of international relief after a disaster is actually creating a disincentive to take appropriate actions in advance of a disaster, the agencies/countries that

[97] http://www.citesciences.fr/francais/ala_cite/science_actualites/sitesactu/question_actu.php?id_article=81&langue=an .

provide disaster relief should be motivated to provide at least some of the funding for an international organization to warn of impending volcanic hazards.

e) Summary

Dangerous volcanic eruptions appear to be relatively predictable, but also relatively uncommon, and the capacity to predict them is not supported by other activities such as weather forecasting. This means that more creative approaches to providing the capacity to predict eruptions may be needed to insure that appropriate actions are taken when an eruption is possible. This would be especially important in less developed countries that are far less likely to have indigenous capacity to predict volcanic eruptions.

V. Appendix 2: Rationale for Hazard Scoring in Table 2

The scoring system in Table 2 is a way of assessing the possible benefits that might be derived from an early warning system for these hazards. This appendix presents the rationale for the judgments that are embedded in the scores assigned in Table 2. For ease of reference, Table 2 is repeated here. The bold text headings that follow Table 2 correspond to the columns in Table 2.

Table 2
A System for Scoring Hazards by Their Likely Benefits – Indian Ocean Region

Scores by Life Saving Benefits	Frequency	Predictability	Severity (loss of life)	Potential Life Saving	Summary
Cyclones	5	5	4	5	4.7
Floods	5	5	2	3	3.5
Volcanoes	2	5	3	5	3.5
Heat	3	5	2	3	3.1
Tsunamis	1	3	5	4	2.8
Tornadoes	2	3	2	3	2.4
Drought	2	2	1	1	1.4
Earthquakes	3	0	5	0	0.0

Scores by Loss Prevention	Frequency	Predictability	Severity (damage)	Potential Loss Reduct.	Summary
Cyclones	5	5	4	3	4.2
Floods	5	5	5	2	4.0
Volcanoes	2	5	2	3	2.8
Drought	2	2	3	1	1.9
Tsunamis	1	3	3	1	1.7
Tornadoes	2	3	2	0	0.0
Heat	3	5	0	0	0.0
Earthquakes	3	0	4	0	0.0

Frequency

1. Note that the numbers in the Frequency and Predictability column are the same in both parts of Table 2. This is because these scores depend on the characteristics of the hazard, and not in any way on whether the concern is saving lives or preventing property damage.
2. According to the EM-DAT database, the most common disasters in the south-east Asia region, from 1970-2008, were as follows:

Floods	404
Storms (primarily cyclones)	363
Seismic[98]	101
Mass movement wet[99]	72
Volcano	52
Drought	39
Mass Movement Dry[100]	6

Source:
http://www.emdat.be/Database/AdvanceSearch/emdat_chooser.php
http://www.emdat.be/Database/AdvanceSearch/emdat_chooser.php

These data suggest that in the Indian Ocean region, Cyclones and Floods are by far the most frequent natural hazards, justifying a frequency score of 5 for these hazards. Seismic events (mostly earthquakes) are a distant third, suggesting a score of 3, volcanoes and drought are significantly less common that seismic, leading to a score of

[98] Tsunamis are treated as a subset of seismic disasters in the EM-DAT database. Tsunamis are not easily broken out from the overall class of seismic disasters in that database, but tsunamis are rare in the Indian Ocean, and the December 26, 2004 tsunami is likely the only one in this group.

[99] In most cases, Mass Movement Wet will result from a weather event such as a cyclones or other heavy precipitation often associated with flooding.

[100] Earthquake is the most likely cause of Mass Movement Dry.

2. Since there is probably only 1 tsunami (included in the seismic category), tsunami is given a frequency score of 1.

3. Extreme Temperature is a disaster type that is tracked by the EM-DAT database. This disaster type includes both extreme heat and extreme cold. However, Extreme Temperature does not appear in the disaster list above. This is most likely a bug in the EM-DAT system, since an Extreme Temperature (heat) event does appear as one of the ten worst disasters in India over the time period 1980-2008 (see below). In the United States, extreme heat has only recently been recognized as a serious threat, and it may be that reporting of this type of disaster is still rough and uneven. Based largely on the evidence that extreme heat events are quite common in the United States, these events are assigned an intermediate frequency score of 3.
4. The EM-DAT category "Storms" includes cyclones, tornadoes, and other wind events. There is no way to easily break out these various wind events in the summary data above. However, tornadoes are not likely to be common in the Indian Ocean region, despite the fact that they are common in the United States. In the United States, 800 tornadoes are reported in an average year. While this number is far in excess of the number of cyclones that make landfall in the US, many of these tornadoes do little damage. If attention is restricted to tornadoes that do serious harm, the frequency in the US might be about the same as the frequency of cyclones in the US. However, the central section of the United States is an ideal breeding ground for tornadoes; 75% of the world's reported tornadoes occur in the US (and a substantial fraction of the remainder occur in southern Canada). These considerations lead us to believe that tornadoes are likely to be a relatively uncommon threat in the Indian Ocean region. Thus tornadoes are given a frequency score of 2.

Predictability

1. Predictability scores are assessed largely on the basis of the ability to predict these hazards in developed countries such as the United States. This is because there is no reason why the same quality of predictions could not be achieved, albeit at some cost, anywhere else in the world.
2. Weather events in general are quite well predicted by modern weather forecasting systems. For example, a few days warning can be given, with reasonable accuracy, for cyclone landfalls. If there is an exception to this, it may be in tornado prediction, which is somewhat more challenging than prediction for other kinds of weather events. Based on these observations, predictability scores of 5 are assigned to cyclones, floods, and heat; and a predictability score of 3 is assigned to tornadoes.
3. Drought is a special kind of weather event in that severe droughts may last months or years, and our ability to forecast weather over this kind of time frame is quite limited. For this reason, drought is given a predictability score of 2.

4. Of the geologic hazards, volcanic eruptions are the easiest to predict, and these are assigned a predictability score of 5.
5. At the other end of the spectrum, earthquakes are essentially unpredictable at this time, and thus are assigned a predictability score of 0.
6. In between, are tsunamis. Predictability of tsunamis is highly variable depending on the distance between the earthquake that causes the tsunami and the location that will be affected by it. It some instances, the time between the (unpredictable) earthquake and the resulting tsunami is a few minutes; in other cases, it may be several hours. As a compromise, we give tsunamis a predictability score of 3.

Severity – Loss of Life

1. The EM-DAT database retrieval system can easily produce data on the top ten hazards by country, but the same data for an aggregation of countries is not easy to obtain. Thus, data on hazards in India is used to assess hazard severity (because India is a large, important, centrally located country in the region).
2. The following tables show the ten worst disasters in India, by number of lives lost.
3. An earthquake and a tsunami top the list, and these are assigned a severity score of 5.
4. Cyclones are in third and seventh places, and cyclones are assigned a severity score of 4.
5. A heat wave is in eighth place and floods are in ninth and tenth places: these are both assigned a score of 2.
6. Drought does not appear on this list at all, and there is no reason why drought should cause loss of life, so drought is assigned a score of 1.
7. Volcanoes do not appear on the list, but this is most likely because they are uncommon. Volcanoes can be quite deadly, if there no evacuation of people at risk. Volcanoes are given a severity score of 3.
8. Tornadoes also do not appear on this list, and this may be because they are rare, or because they do not cause large loss of life relative to this other hazards on the list. In the US, where tornadoes are common, they are quite deadly. Thus tornadoes are given a severity score of 2, the same as heat and floods.

Table
Top 10 Disasters in India, 1980-2008, by Lives Lost

Disaster	Date	Lives Lost
Earthquake	26/01/2001	20005
Earthquake - Tsunami	26/12/2004	16389
Storm - Cyclone	28/10/1999	9843
Earthquake	29/09/1993	9748
Epidemic	May-84	3290
Epidemic	Nov-88	3000
Storm - Cyclone	9/6/1998	2871
Temperature - Heat Wave	26/05/1998	2541
Flood	May-94	2001
Flood	Aug-98	1811

Severity – Damage

1. The table below shows the ten worst disasters in India, measured by dollar damages from 1980-2008.
2. Although floods were at the bottom of the list of disasters ranked by loss of life, floods dominate the list of disasters ranked by dollar damages, with ranks 1-3, 6, 7. Floods are given a severity (damage) score of 5.
3. The worst earthquake and the worst cyclone are about equal in damages, and both less than half the damage of the worst flood. Earthquakes and cyclones are assigned a severity score of 4.
4. The tsunami of 2004 is last on this list. It is given a severity score of 3.
5. Although it did not make the top 10 list, there was a drought in 2002 with estimated damages (in thousands US$) of 910722, which is just barely below the damages from the 2004 tsunami. Based on this observation, drought is also assigned a severity score of 3.
6. There were no volcanic eruptions of note during this time period in India. Although volcanic eruptions can devastate property in its path, it seems likely that the value of property close to volcanoes is less than the value of property at risk from cyclones, since coastal settlement is generally much denser and wealthier than settlement around volcanic mountains. Based on this observation, volcanoes are assigned a severity score of 2.

7. Tornadoes tend to be very local in nature, and for this reason are also likely to be less damaging than most of the other hazards. For this reason, tornadoes are also assigned a severity score of 2.
8. Heat is assigned a severity score of 0, since heat does not damage property in any significant way (except to the extent that it is associated with drought, which in any case is separately considered).

Table
Top 10 Disasters in India, 1980-2008, by Monetary Damage (US$ in year of occurrence)

Disaster	Date	Damage US$ (000)
Flood	8/7/1993	7000000
Flood	28/07/2006	3390000
Flood	24/07/2005	3330000
Earthquake	26/01/2001	2623000
Storm – Cyclone	28/10/1999	2500000
Flood	20/06/2004	2500000
Flood	28/06/2005	2300000
Storm – Local	25/08/1990	2200000
Storm – Cyclone	6/11/1996	1500300
Earthquake - Tsunami	26/12/2004	1022800

Source:
http://www.emdat.be/Database/CountryProfile/countryprofile2.php?disgroup=natural&country=ind&period=1980$2009

Potential Life Saving

1. Potential life saving here means the likelihood that an early warning system can save lives. The scoring judgments made here are largely based on evidence from the United States about the extent to which warning systems save lives in the case of each of the hazards.
2. The highest score (5) is given to cyclones and volcanoes. Cyclones get this score because their landfalls can be predicted quite well a few days ahead of the event, and with this lead-time, it is not difficult to evacuate people to safer locations. Volcanoes

can also be predicted with plenty of lead-time to evacuate people, even though the precise time of a volcanic eruption cannot be as accurately predicted as the precise time of a cyclone landfall. Evacuations themselves are costly, but not difficult to implement if residents in a threatened area are willing to heed the warning.

3. Tsunamis are given a score of 4. They can be well predicted, though not with the amount of lead-time as is the case for cyclones and volcanoes. Lead-time may average a few hours, though it should be recognized that for some people at risk, the lead-time can be just minutes, really too little to have an effective mass evacuation.
4. Floods are given an intermediate score of 3. Floods, other than flash floods, can be predicted very well, with days of lead-time. Flash floods, however, are very difficult to predict, and any predictions given are likely to have just minutes of lead-time. Flash floods are difficult to predict because they depend on the precise location of heavy rainfall, relative to local topography, as well as on local soil saturation conditions.
5. Heat is given an intermediate score of 3. While heat is very easy to predict, it is not so easy to protect the vulnerable from heat. This is because vulnerable people may not even realize that they are at risk, heat being a commonplace phenomenon and one that poses no real threat to healthy people. For this reason, it may be difficult to get an appropriate response to warnings.
6. Tornadoes are given an intermediate score of 3. Predicting the existence of conditions that might produce tornadoes is easy, but predicting the actual occurrence of a tornado is very hard. While advanced radar system can sometimes identify an emerging tornado, often tornados are not predicted so much as they are observed, either by radar or by people on the ground. As a result, tornado warnings tend to have just a few minutes of lead-time, and this makes it difficult to communicate the warning and get people to safety in time.
7. Drought is given a low score of 1. This is because there is no real reason why drought should lead to any mortality, if there is an effective and timely response to drought. Having an early warning of drought might make it a little cheaper to respond, but it is a stretch to think that an early warning system by itself is likely to make much difference in the number of lives lost to drought.
8. Earthquakes are given a score of 0. Since earthquakes are essentially unpredictable, they will have a summary score of 0 anyway. If one cannot predict earthquakes, there is no reasonable way to speculate on how many lives would be saved by an early warning system

Potential Loss Reduction

1. The highest score in this column, a 3, is assigned to cyclones and volcanoes. These can be predicted quite well with a few days lead-time. Mobile property (e.g. airplanes, cars) can be moved out of harm’s way. However, there is not a lot that can be done to protect

other property, except small items that can be carried out during an evacuation. The potential to protect property from a cyclone or volcano is decidedly lower than the potential to protect lives, and for this reason, a score of 3, rather than 5, is assigned.

2. Floods are assigned a lower score of 2. River floods can be predicted with lead-time much like that for cyclones, but flash floods will have very little lead-time, and not enough to protect property. For this reason, floods are assigned a lower score than cyclones and volcanoes.
3. Tsunamis are assigned an even lower score of 1, because the average lead-time for a tsunami warning is lower than the average lead-time for a flood.
4. Droughts are also assigned a lower score of 1, based on a judgment that the assets at risk from a drought (primarily crops) are difficult to salvage, even if there is a very substantial lead-time for a drought warning.
5. Tornadoes and earthquakes are assigned scores of 0. In the case of tornadoes the lead-time is too short to do anything except protect lives. In the case of earthquakes, which are essentially unpredictable, there is no lead-time.
6. Heat is also assigned a score of 0, because heat does not affect property (except through them mechanism of drought, which is treated separately).