

Communicating Uncertainties in Natural Hazard Forecasts

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Natural hazards research seeks to help society develop strategies that appropriately balance risks and mitigation costs in addressing potential imminent threats and possible longer-term hazards. However, because scientists have only limited knowledge of the future, they must also communicate the uncertainties in what they know about the hazards. How to do so has been the subject of extensive recent discussion [Sarewitz *et al.*, 2000; Oreskes, 2000; Pilkey and Pilkey-Jarvis, 2006].

One approach is General Colin Powell's charge to intelligence officers [Powell, 2012]: "Tell me what you know. Tell me what you don't know. Then tell me what you think. Always distinguish which is which." In dealing with natural hazards, the last point can be modified to "which is which and why." To illustrate this approach, it is helpful to consider some successful and unsuccessful examples [Stein, 2010; Stein *et al.*, 2012].

Short-Term Forecasts: Snowstorms, Hurricanes, and Tsunamis

Meteorologists have taken the lead in explaining uncertainties in forecasts to the public [Morss *et al.*, 2008; Hirschberg *et al.*, 2011]. For example, on 2 February 2000 the *Chicago Tribune* stated, "Weather offices from downstate Illinois to Ohio advised residents of the potential for accumulating snow.... But forecasters were careful to communicate a degree of uncertainty on the storm's precise track, which is crucial in determining how much and where the heaviest snow will fall. Variations in predicted storm tracks occur in part because different computer models can infer upper winds and temperatures over the relatively data-sparse open Pacific differently. Studies suggest that examining a group of projected paths and storm intensities—rather than just one—helps reduce forecast errors." Graphics compared four predicted storm tracks and seven precipitation estimates for Chicago, Ill.

In the Powell formulation, "what you know" is that a storm is coming; "what you don't know" is its exact track and thus how much snow will fall where, illustrated by the comparison of the varying model predictions; "what you think" is that snow accumulation is likely; and "which is which and why" are the models' uncertainties and their limitations, due, in part, to sparse data.

In another example, as Hurricane Irene threatened the U.S. East Coast, a CNN article explained that "We do not know for sure whether Irene will make landfall in the Carolinas, on Long Island, or in New England, or stay far enough offshore to deliver little more than a windy, rainy day to East Coast residents. Nor do we have better than a passing ability to forecast how strong Irene will get. In spite of decades of research and greatly improved observations and computer models, our skill in forecasting hurricane strength is little better than it was decades ago" [Emanuel, 2011]. The article described the causes of uncertainty and approaches being taken to address it.

Conversely, warnings or forecasts that do not communicate uncertainties can have embarrassing and sometimes counterproductive results. In 2008, as Hurricane Ike approached the Texas coast, the National Weather Service warned that people who did not evacuate coastal communities faced "certain death." In fact, fewer than 50 of the 40,000 who stayed on Galveston Island were killed. The predicted 100% probability of death—stated with no indication of uncertainty—fortunately proved significantly too high.

The trade-off is that worst-case warnings may save lives, but repeated overpredictions that do not acknowledge uncertainty can cause the public to ignore warnings. Of the residents who heard the "certain death" warning, about equal numbers had positive and negative impressions [Morss and Hayden, 2010]. Positive responses included "blunt... effective," "correct," "to the point," "scared you to death," and "people who didn't heed were foolish." Negative responses included "harsh and overreactive," "overblown," "ridiculous," "humorous," "stupid," "rude," and "not appropriate." Morss and Hayden concluded

that the "certain death" warning helped persuade some to evacuate while making others who considered it "overly dramatic or not credible" less likely to respond to future warnings. Hence, it is desirable to issue more nuanced warnings that explain the potential danger while acknowledging the uncertainty.

A similar situation arises for tsunami warnings. Many lives were saved by the warnings following the 2011 Tohoku earthquake and tsunami. However, some tsunami hazard maps were based on the run-up data for large tsunamis that occurred only in the past 150 years and thus misidentified areas farther inland as safe. In addition, some residents ignored the warning because of past false alarms. In the previous 4 years, 16 warnings or alerts had been issued for "small or even negligible tsunamis. These frequent warnings with overestimated tsunami height influenced the behavior of the residents" [Ando *et al.*, 2011]. As noted by tsunami researcher Costas Synolakis after parts of Honolulu were evacuated in anticipation of a tsunami in February 2010 that turned out to be small and harmless, as predicted by tsunami modeling, "Every ounce of extra prevention is counterproductive as it reduces the overall credibility of the system" [Schiermeier, 2010].

Longer-Term Forecasts: Climate Change and Earthquake Hazards

Although the issues in longer-term forecasts are more difficult to explain than for short-term forecasts of an ongoing event, similar approaches can be taken. The *Intergovernmental Panel on Climate Change (IPCC)* [2007] report compares the predictions of 18 models for the expected rise in global temperature. Models developed by groups using different methods and assumptions are shown (Figure 1a) and discussed in the report. The report further notes that the models "cannot sample the full range of possible warming, in particular, because they do not include uncertainties in the carbon cycle."

A similar approach could be used for earthquake hazards, which are traditionally presented by a map showing "the" hazard—the shaking expected with some probability in some time interval. In reality, such maps often have large uncertainties because they depend on many poorly constrained parameters [Stein *et al.*, 2012]. As a result,

they often prove inadequate, as illustrated by destructive earthquakes—including the 2011 Tohoku, 2010 Haiti, and 2008 Wenchuan events—that occurred in areas predicted to be relatively safe [Kerr, 2011]. Analyses of large earthquakes worldwide find that the shaking is often significantly higher than predicted [Kossobokov and Nekrasova, 2012] and so causes many more fatalities than expected [Wyss *et al.*, 2012].

Thus, it would be more useful to show a range of predictions. Figure 1b compares hazard predictions for two cities in the central U.S. New Madrid Seismic Zone. These vary depending on the assumed magnitude of the largest earthquakes ($M7$ or $M8$), the model chosen to predict ground shaking (“Frankel” or “Toro”), and whether the probability of the largest earthquakes is assumed to be time independent (TI) or time dependent (TD)—small shortly after one has occurred and then increasing with time.

Challenges

One major challenge is that real uncertainties often turn out to have been underestimated. In many applications, 20%–45% of results are surprises, falling outside the previously assumed 98% confidence limits [Hammit and Shlyakhter, 1999]. A famous example is measurements of the speed of light, in which new and more precise measurements fell outside the estimated error bars of the older ones much more frequently than expected [Henrion and Fischhoff, 1986]. This effect arises in predicting river floods [Merz, 2012] and earthquake ground motion and may arise for the IPCC uncertainty estimates [Curry, 2011].

Another tough challenge, for which scientists do not yet have a good approach, involves extreme events that are so rare that their probabilities are hard to estimate. The 2011 Tohoku earthquake was much larger than considered in the Japanese government’s hazard map [Geller, 2011; Stein and Okal, 2011] and so caused a tsunami that overtopped seawalls, causing more than 18,000 deaths and \$210 billion in damage. An immediate question is if and how coastal defenses that fared badly should be rebuilt, because building them to withstand tsunamis as large as 2011’s is too expensive. A similar issue arises along the Nankai Trough to the south, where recent warnings of tsunamis 2–5 times higher than in previous models raise the question of what to do, given that the time scale on which such events may occur is unknown but may be on the order of 1000 years [Cyranoski, 2012]. In one commentator’s words [Harner, 2012], “The question—to be asked in the current case—is whether sometimes the bureaucratic impulse [to] avoid any risk of future criticism by presenting the ‘worst case scenario’ is really helpful...What can (or should be) done? Thirty meter seawalls do not seem to be the answer.”

Formulating effective mitigation strategies is both an economic and political

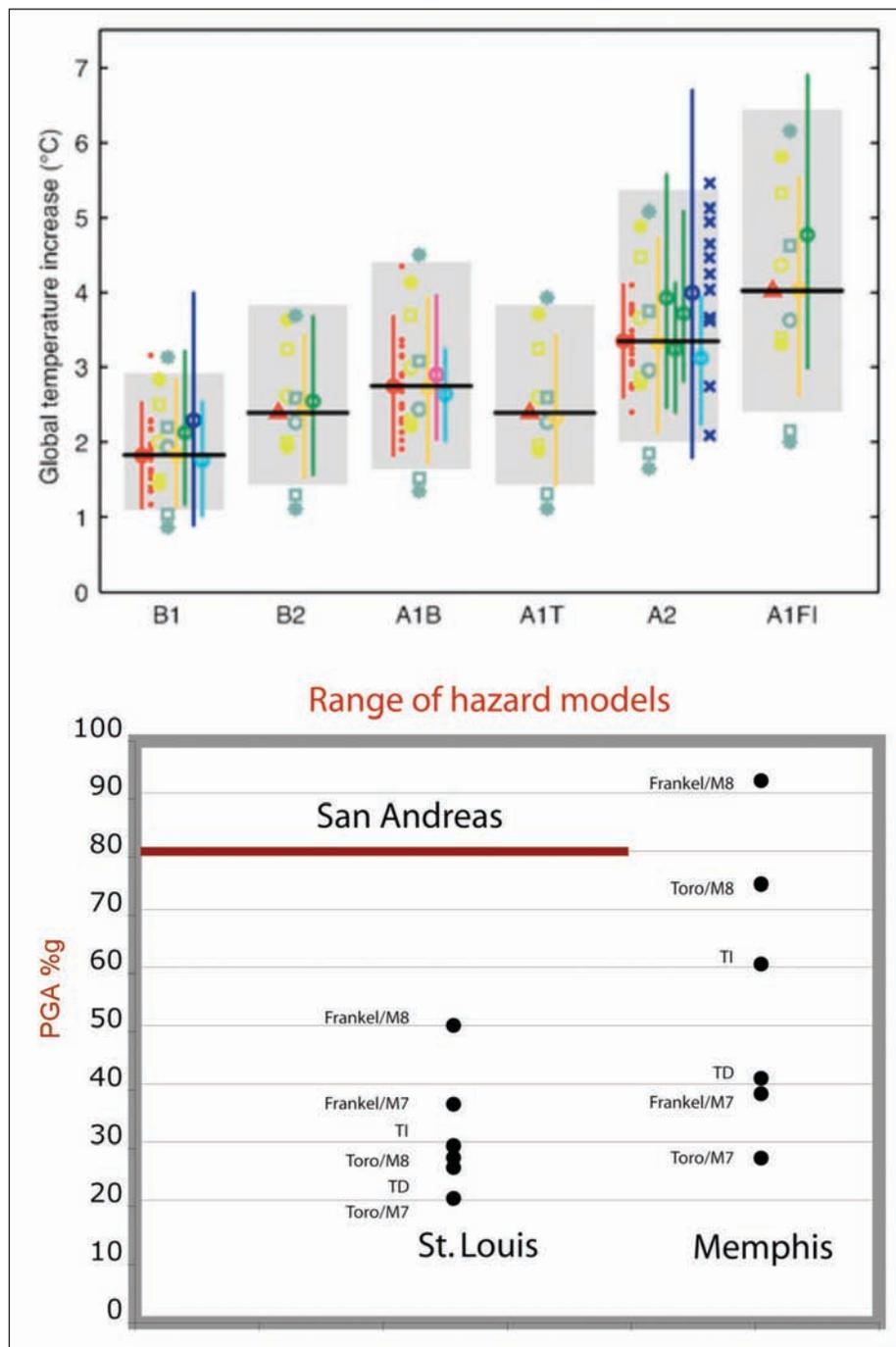


Fig. 1. (top) Comparison of the rise in global temperature by the year 2099 predicted by various climate models. For various scenarios of carbon emissions, e.g., B1, the vertical values show the range of predicted warming [IPCC, 2007]. (bottom) Comparison of earthquake hazard, described as peak ground acceleration (PGA) as a percentage of the acceleration of gravity expected with 2% risk in 50 years, predicted by various assumptions for two sites in the central United States [Stein *et al.*, 2012].

challenge. In both spheres, explaining the uncertainties involved in hazard forecasts is crucial, even though they cannot be precisely estimated. From an economic viewpoint, they can be factored into analyses of the optimum mitigation level, i.e., that which minimizes the total cost to society, which is the sum of the cost of mitigation and the expected losses [Stein and Stein, 2012]. Presenting the uncertainties is equally important for the public discussion

needed to formulate policies. Sarewitz *et al.* [2000] argue that predictions must be as transparent as possible; that assumptions, model limitations, and weaknesses should be forthrightly discussed; and that uncertainties must be clearly articulated.

A similar view of the need for explaining uncertainties comes from considering technological accidents, which are like natural disasters in that the risks are hard to assess but can be large. Richard Feynman,

dissenting from the official report after the loss of the space shuttle Challenger, showed that the risks had been greatly underestimated and stated that "NASA owes it to the citizens from whom it asks support to be frank, honest, and informative, so these citizens can make the wisest decisions for the use of their limited resources" [Feynman, 1988]. Scientists working on natural hazard forecasting should consider Feynman's advice.

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