Elements of a Severe Climate Change Early Warning System

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Abstract

A skillful early detection and warning system for severe and/or abrupt climate change would benefit both adaptation and geo-engineering interventions. But what would a severe climate change early warning system look like? Important characteristics of dangerous climate shifts, like rate of onset, intensity, spatial distribution, and predictability, are poorly known but are the subject of growing research efforts. Some *ad hoc* forms of early warning are already emerging, and attention now to the elements of effective natural hazard warning systems would seem prudent. The nature of warnings for hazards like hurricanes, volcanoes, and asteroids is examined for lessons relevant to a climate change early detection and warning system. An initial analysis of the relationships among lead time, warning, and response for different profiles of severe climate change is offered.

Key words: warning systems; severe climate change; decision making.

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1. Introduction

Natural and anthropogenic climate change could yield a range of threats to social well-being, from severe, abrupt events, like sharply colder epochs (e.g., the Little Ice Age) or strings of heat waves, to irreversible long-term trends like ice sheet disintegration (Arnell et al. 2005; Schellnhuber et al. 2006). Most of the contemporary concern about extreme climate swings is associated with anthropogenic global warming. Growing apprehension that mitigation cannot keep global warming below dangerous levels (Arnell et al., 2005; Parry et al. 2009; Schneider 2009; New et al., 2011) leads logically to calls for more attention to adaptation and to potential geo-engineering interventions at least to slow the warming and allow mitigation to take hold, and "just in case" we face climate emergencies (Schneider 2008; The Royal Society 2009; National Research Council 2010). Both adaptation and geo-engineering would need information and decision support (National Research Council 2009), such as systems that could detect and warn about impending severe changes in the climate system (e.g., ice sheet collapse, regional flips to more arid climates, etc.) with some skill and at some policy-relevant lead time (Lenton et al. 2008).

At first glance the notion of creating a system for warning of impending severe climatic changes might seem far-fetched, as well as fraught with ambiguity. The population of potentially severe climate sequences, their magnitudes, rates of onset, and geographical distribution of impacts, are as yet poorly discerned. But, in some ways we already receive "warnings" of climate change via the reports of the Intergovernmental Panel on Climate Change (IPCC), and more compelling sources such as full-length films (Gore 2006). Yet most extant warning systems attend to discrete, short-term events, like floods, hurricanes, tsunami or volcanic eruptions, and climate change seems out of place in this line-up of recurring phenomena. Moreover, in a changing climate one might expect that warning systems already in place for atmospheric hazards like heat wave would, presumably, simply yield more (or fewer) warnings as underlying climate change increases (or decreases) their frequency.

As concerns about specific severe and/or abrupt changes in the climate system increase (National Research Council 2002; Lenton et al. 2008; Schellenhuber et al. 2006), and as ideas emerge for intervening in global warming through geo-engineering at least as a last resort (Cicerone 2006; The Royal Society 2009), it seems inevitable that some form of climate change early warning system will emerge. The broad experience in hand with hazard warning systems, the awkward history of systems that evolved haphazardly over time, and the complexity of the prediction and warning enterprise, point to the value of assessing that experience and examining its applicability to climate change before we find ourselves with a *de facto*, poorly performing climate change warning system.

2. Extant Early Warning Systems

Warning systems include much more than just alert dissemination, and include detection, analysis, prediction/forecasting, and then warning followed by response decision-making (Mileti 1999; Sorenson 2000; Basher, 2006; Glantz 2009). Systems are in place, in many parts of the world, to monitor, forecast, and warn people about tropical cyclones, floods, winter storms, tsunami, avalanches, tornadoes, severe thunderstorms, volcanic eruptions, and extreme heat and cold (Zschau and Küppers 2003; Glantz 2009). Given limits on predictability, some of these systems stress real-time early detection and now-casting ("warn on detection") while others are more firmly based on forecasts *per se* ("warn on prediction").

Warning systems attempt to deliver three key types of information: (1) the physical nature and magnitude of the event, (2) timing and duration, and (3) location (thus the popular phrase: what, when and where), all with some skill above chance or climatology and with sufficient lead time to be useful. The level of resolution and uncertainty varies substantially across systems and their components. Warning systems further struggle with formulation and dissemination of the warning message itself, and the meaning and usefulness of warnings for different types of users.

2.1 The Event

The seemingly obvious question of just what "event" is forecast can be problematic in many types of natural hazard warnings. Researchers have found differences between what technical analysts and the public envision as the predicted event in many types of public warnings (Sorenson 2000). In early studies of probabilistic precipitation forecasts, researchers found variation among forecasters, and between forecasters and forecast users, in interpretation of what constituted a precipitation event (Murphy 1994). El Nino-La Nina advisories might make sense, say, to fishermen in coastal Peru, but what about residents of the southern U.S. (Glantz 2001)? Even something as concrete as a hurricane warning can be interpreted in various ways (Broad et al. 2007). And most hazards are actually ensembles of various elements. A hurricane comes with storm surge, wind, heavy rain, flooding, and tornadoes. A single volcano can threaten lava flows, pyroclastic flows (usually the most deadly threat), ash fall, aviation ash hazard, landslides, earthquakes, and mudflows (lahars). Thus warnings have become increasingly segmented into suites of associated events and their localized impacts.

Many warning systems rely on a quantitative scale for expressing the intensity of geophysical events, well-known versions including the Safir-Simpson Scale for tropical cyclones (founded on wind speed and central pressure) and the Fujita Scale for tornadoes (based on assumed wind speeds, but, like Safir-Simpson, also based originally on damage thresholds). Some warning systems involve detailed resolution to particular magnitudes in particular settings: the tsunami warning system in the Pacific Ocean attempts to translate the relatively easily-predicted propagation of a wave across the ocean into the wickedly-difficult prediction of likely wave heights and run-up distances at selected coastlines, each segment of which responds differently to the wave train.

2.2 Timing

Temporal elements of forecasts and warnings are especially critical to decision-making. All warning systems exhibit an inverse relationship between lead time and accuracy and specificity, and with the difficult balance of type I and type II errors (e.g., forecasters have to worry both about false positives, that yield over-warning, and false negatives, that yield under-preparedness). Warning systems involve complex interactions (and trade-offs) among reliability, skillful lead time, desired lead time for social response, and event onset profiles. Earthquakes anchor the low forecast skill/rapid onset end of the spectrum, and the few extant earthquake warning systems are based on real-time detection and transmission of alerts faster than the damaging waves can propagate to provide a few seconds of warning (Allen et al., 2009; Allen, 2011). Winter storms, hurricanes, and riverine floods offer relatively high skill and medium onset times (hours to days), thus yielding useful warnings lead times. Some volcano eruptions and most droughts offer little forecast skill but relatively long onset, thus allowing useful, long-term now-casting. Warning systems have, logically, focused on high-impact hazards, for which decision-makers would want as much time for preparation as possible, thus there is constant pressure to extend lead times. Usefulness depends on the decision context: the timing of some "go" decisions, like evacuating a city in front of a hurricane, is set by factors (e.g., population and transportation routes) unrelated to the forecast problem (Baker 2000; Lindell et al. 2007). But extended lead times almost certainly mean more false positive errors which, in the case of hurricane evacuations, can be quite costly (Pielke, Jr. and Carbone 2002).

2.3 Location

Ambiguities in traditional warning messages about location (e.g., flooding of "low lying areas") have been reduced with details and resolution allowed by Geographic Information Systems (GIS), high-resolution models like storm surge simulations, and in some cases address-specific advisory systems. Still, many forecast and warning systems must issue geographically-broad advisories, especially at longer lead times, due to uncertainty and a preference against under-warning. Long segments of coastlines and large polygons of territory are routinely warned about severe weather; tsunami alerts often apply at the ocean basin and continental scale. Even in the case of hazards like volcanoes, which would seem geographically well nailed-down, the location dimension may be infused with uncertainty. A roughly concentric evacuation zone was designated around Mt. Ste. Helens, which, in 1980, sent a horizontal blast well outside the warning area along a northward azimuth (Lipman and Mullineau 1981).

2.4 Skill and Usefulness

All hazard warnings inculcate significant magnitude, temporal, and geographical uncertainty, and limits on forecast skill restrict warnings mostly to categorical expression in two to three tiers typified by the well-known “watch” and “warning” vernacular applied to many atmospheric hazards. “Warning” is usually reserved for high confidence impact (systems for tornadoes, flash floods, and mudflows reserve the term until the event is detected and underway). Only a very few systems, in limited locales, include probabilistic information to convey uncertainty (e.g., hurricane strike probabilities; see Sheets 1985; Willoughby et al. 2007).

The concepts of forecast and warning accuracy, value, and usefulness are themselves ambiguous, and frequently mis-understood, even by relatively sophisticated users (Katz and Murphy, 1997). The basic framework for analyzing the value of weather predictions and warnings was worked out in the 1950s and 1960s in foundational papers by Thompson and Brier (1955) and Thompson (1963), and applied to several types of weather-sensitive decisions (e.g., Murphy, 1977; 1994; Katz and Murphy 1997), and later to seasonal forecasts (see: Stern and Easterling 1999). The formulation by Thompson and Brier was deceptively simple and included the probability of adverse conditions (*p*) compared to the ratio of the costs of protecting against those conditions (C) and the losses (L) incurred if no protective action is taken and the conditions occur. If $p<C/L$ then it makes sense not to protect (do protect if $p>C/L$). The subtle element here is that forecast value must be measured as an increment of improvement not only above chance, but over climatology, and the net value is the difference of losses and gains including costs expended when no adverse conditions occurred but $p>C/L$, as well as the losses incurred when adverse conditions did occur but the forecast *p* was less than the cost-to-loss ratio.

Thompson also showed that forecast value varies across the underlying probabilities, so that at very low and very high climatological likelihoods of adverse conditions, tuning of the operation to the average expected state (never protect or always protect) could yield more benefits than investing in better forecasts. Murphy and Ehrendrofer (1987) later showed that depending on how forecast accuracy is measured, realistic decision cases exist where increased accuracy does not yield increased value (see also: Millner 2009). These and other interactions of forecast accuracy and utility explain why intuitive expectations of the benefit-cost ratio of forecast and warning improvements are not always supported by socio-economic analysis (Pielke and Carbone 2002); this may apply especially to warnings situations (as opposed to routine forecasts) because of the inherent risk aversion in the decisions to be made: the added benefit of improved hurricane forecasting that allows, say, smaller areas to be warned 24 hours in advance of landfall, may be discounted by the decision-maker compared to the feared cost of having a hurricane hit an area that was not warned at least 24 hours in advance (though little research exist to illuminate this widely asserted effect; for a review see: Lindell et al. 2007). In many warning situations costs and losses do not follow the same subjective utility function (Letson et al. 2007).

2.5 Other Social Dimensions

Despite decades of experience with geo-physical warnings, we are just beginning to appreciate the complex social dimensions that bedevil warning systems, and factors that sometimes yield bad decisions from good predictions (Pielke at al. 2000). The "prediction enterprise," with which we so often respond to environmental uncertainty and risk, is so complex a social process that it cannot always be counted on to yield useful outcomes even as the science improves (Dessai et al. 2009 and Charlesworth et al. 2009). Because warning systems exist to serve particular human needs, their design, operation, and effectiveness is sensitive to social setting, user needs, and response issues, like necessary evacuation times (Sorensen, 2000; Basher 2006), and to the many social dimensions of risk such as differential vulnerability and adaptive capacity across groups and places (Cutter et al. 2003; Tierney et al. 2001), which, of course, would apply to climate change warnings.

3. Models for Climate Warning Systems

The complexity and challenges of current monitoring and warning systems for natural hazards hint at the many issues that will arise if we decide that climate change warnings are necessary, but also suggest that such warnings pose no particularly unique design problems. What would a severe climate change warning look like? The scientific and technical basis for some type of climate change warning is emerging slowly (and not addressed in this paper), but attention now to a prototype advisory system may save problems down the line.

Good and bad experiences in other warning systems will prove educational, and a few extant systems offer useful models, especially, for example, el Nino advisories (Glantz, 2001), drought and other seasonal predictions (Stern and Easterling 1999), and famine early warning (Glantz et al. 2009). NOAA's El Nino advisories (http://www.cpc.noaa.gov/products/analysis_monitoring/lanina/) offer something of a prototype climate change warning system: they include now-casting and projections of El Nino conditions, linked to discussions of what those conditions could mean for regions of the U.S.

One little known, nascent hazard detection and warning system, the Near Earth Object (NEO) survey and associated Torino Scale (http://neo.jpl.nasa.gov/torino_scale.html) (Fig. 1a) for potential asteroid impacts on Earth (Morrison et al. 2004), offers several lessons for climate change advisories. The Torino Scale includes triggers for action to physically intervene in the threat, as would be needed for geo-engineering. Like some gauges of volcano risks (Fig. 1b), the Torino Scale is designed to deal with multiple threats over long-time horizons, and to vary as additional information is collected about a given, threatening asteroid over periods of years to even decades, bringing it into the temporal realm of climate change tipping elements. The scale's threat level is a product of probability of impact and potential effects, which are based on size, composition, speed, and likely impact location. The rating of a particular asteroid might increase or decrease as more information about it becomes available. The threat is arrayed on a 10-point scale meant to evoke increasing response as risk escalates: first to instigate more monitoring and analysis (e.g., more effort to track and size the object) and, eventually, actions to try to prevent the impact. As such the Torino Scale is a good model for severe and abrupt climate change: elements of concern, like ice sheet disintegration, could be codified and their likelihood and impacts assigned a threat level and refined over time as knowledge improves and monitoring data streams in (Lenton et al. 2008).

Extant systems also reveal pitfalls of hazard warnings. Early applications of the Torino Scale had an unnerving tendency to yield rather high threat levels for newly-discovered near-earth objects, which were dutifully reported by the media but invariably declined as more data were collected. Hurricane strike probabilities used in the U.S. have had something of the opposite problem: as the hurricane track forecast cone intersects a coastline, the probabilities are spread out across so many pre-set coastal segments that the value for any one area remains quite low, and only rises to what a lay-person might take as worrisome just before landfall (Baker 2000 317). In its inception, the strike forecasts were precluded, by design, from probabilities greater than 50% until within 24 hours of landfall (Sheets, 1985; strike probabilities have now been replaced with wind speed probability forecasts; see Rappaport et. al. 2009). And a hurricane strike forecast is about both *where* and *when*; hurricanes can slow or accelerate in forward motion without changing track (or intensity), so the event is going to happen, only delayed or advanced, and thus time-anchored response decisions might need to be adjusted while strike probabilities remain the same. The U.S. Geological Survey (USGS) experiment with geologic hazard warnings, first for the Long Valley Caldera volcano in California, threw into question the usefulness of the tiered watch-warning approach for threats that evolve over years and decades (Fig. 1b). Increased seismic activity in the early 1980s led to issuance of the first volcano hazard "watch;" but as the watch dragged on for months without an eruption, and with the prospect for years of alerts as swarms of small earthquakes came and went, affected communities felt that the approach could dampen the local economy and the U.S.G.S. re-designed the system with "stand-down" criteria so communities would not be left hanging in a warning (Hill et al. 2002). Can we avoid these pitfalls in a climate change early warning system?

4. Emerging Forms of Climate Change Warning

In a sense the global community is already receiving "warnings" of climate change (Gore 2006), and in some cases they are quite specific, including maps of areas to be inundated as sea levels rise, and likelihood of water shortages or altered flood return intervals (Parry et al. 2008). The local emergency manager struggling to get the public to pay attention to the current flood hazard, or to the long-term risk posed by a nearby volcano, might envy the exposure now accorded global warming. But no formal climate change warning system is in place. During most of its historical emergence as a threat, the dominant conceptualization of global warming has been of cumulative, relatively slow change over time; attention to potentially abrupt, severe change is more recent. Moreover, climate scenarios conveyed in the IPCC and other assessments (e.g., Meehl et al. 2007), are typically couched not as predictions *per se*, but as "projections" or "scenarios," words chosen to deny that they might be actual forecasts or warnings. These geo-physical projections have the unusual quality that they are designed to lay out a potential future so that *action can be taken now to negate the projection*. As Parry et al. (2008) noted, until recently it was considered "defeatist" to interpret global warming projections as future conditions expected actually to verify, for which to prepare, as opposed to outcomes that could and should be prevented by changing human behavior and technology. But, as they and others now argue (Pielke et al., 2007; Schneider, 2009), significant anthropogenic global warming appears to be inevitable, is already expressed in climate changes in some places (IPCC 2007; Karl et al. 2009), and a trend toward worsened expectations is now well established in lay and technical discourse.

In a world already awash in climate change foreboding this brief discussion will be limited to projections that take on the rough form one expects of a formal warning. A few have emerged, the most warning-like is the "Reasons for Concern" (RFC) diagram (Fig. 2) in the IPCC's third assessment report (Smith et al. 2001, p. 958) which was up-dated (without the graphic) in AR4's Synthesis Report (2007: 19-20), and up-dated graphically, to quite dramatic visual effect, in Smith et al. (2009).

The RFC graphic is strongly imbued with warning-like iconography; Smith et al. use a long-standing visual warning technique of graded coloration from yellow to red to indicate increasing likelihood of the rated event (at a given threshold of GMT rise above a *circa* 1990 baseline). They choose red to indicate the worst outcomes, as warning convention dictates, and they increase the color saturation to indicate higher "level of risk," though they do not specify whether the term risk is used technically, as a product of likelihood and consequence, or colloquially, as likelihood. Some aspects of the RFC are enigmatic: it mixes the notion of risk implied by the color saturation and risk anchored on the different polar dimension labels inside each column, some of which redundantly infer risk (e.g., "risk to some" vs. "risk to many") or impact (positive to negative). This makes interpretation difficult; for example the "risk of large-scale discontinuities" appears to have shifted to a lower GMT in the 2009 version, according to the red coloration, but the "high" risk label remains fixed at the top of the column, in the 4 to 5 degrees C. range. Now that the reader can compare two versions, the red bar appears to be shifting toward the "low" risk pole, surely not what the authors wished to convey.

In many ways the RFC graphs illustrate common challenges with risk communication that afflict all warning systems, especially when boiled down to a numbered and/or color-coded hierarchy. By attempting to convey several dimensions that they consider important (risk, likelihood, threshold temperature change, and the elements of specific concern, some of which interact) the authors increase message ambiguity. Such risk communication problems show up in many warning systems, including, for example, hurricane strike probabilities that remain quite low for a given coastline segment somewhat removed from the central track but nevertheless subjected to significant storm surge, and the trade-offs among probability, time period, and intensity inherent in USGS earthquake ground shaking risk maps (which also use a yellow-to-red color scheme; see, for example: http://gldims.cr.usgs.gov/nshmp2008/viewer.htm).

These complications notwithstanding, the RFC graph provides a foundation for a global climate change and impacts warning system. So does the latest incarnation of the "Key Impacts" chart employed in the IPCC's AR4 summary for policymakers to compile impacts documented in the assessment arrayed against GMT (IPCC 2007b, p. 16). Parry et al. (2008) transform the chart into something closer to a warning message by overlaying lines projecting impacts at different future times according to assumptions about GHG emission reductions. Parry et al. complete the triplet of warning elements (what, when and where) with regional versions of the "Key Effects" graph similarly demarcated by outcomes for different mitigation efforts, with more highly resolved and regionally-specific impacts (wildfire areas, permafrost thaw depths, etc.).

By linking GMT rise to specific impacts and future conditions, both the RFC and Key Impacts graphics become warning messages, but with the warning contingent on GHG mitigation policy, which modulates GMT. This separates the current state of global warming projections from traditional warnings, where the geophysical event is not subject to human intervention.

As soon as someone or some group with credibility in the climate change community offers a raw probability of reaching a certain temperature at a certain time, the world will suddenly have a true climate change forecast, and, by implication, a warning. The MIT Joint Program on the Science and Policy of Global Change (Sokolov et al. 2009) is very close to doing this, though their projections specifically include no GHG reduction policies, while a more realistic prediction would include at least weak mitigation.

5. Dimensions of a Prototype Severe Climate Change Detection and Early Warning System

Some form of climate change warning will emerge, at least *ad hoc*, as researchers increasingly discover, and learn to predict, likely changes in the climate system, especially if some skill emerges in anticipating severe and/or abrupt change (Scheffer et al. 2009). Given experience with other warning systems, how might we go about framing the *what*, *when* and *where* elements of a climate change warning, assessing skill and value, and linking the warning to decision-making?

6.1 What: The Climate Element

Climate change warnings are likely to remain rather general for some time to come, indeed, they may become *more* general if couched in a warning system for one over-riding reason: a formal warning system represents a contract between science and society, the terms of which require extraordinary care to achieve a balance between over-warning and under-warning tuned to the actions society takes in response to the warning, which can be quite costly and disruptive. Given the dire implications of a warning of severe or abrupt climate change, the early incarnations of a formal warning system might be biased toward vague statements or even type II (false negatives) errors.

At the most general level of abstraction, a basic climate change alert system might start with a categorical ranking of climate change severity similar to other geo-physical scales like the Modified Mercalli ranking of earthquakes. Dovers (2009) and Travis

(2010) have suggested levels of climate change severity based on current variability and working up through levels of change that exceed historical experience and eventually reach into levels imposing catastrophic impacts and requiring transformative adaptation or other extraordinary responses. The Travis (2010) scale is laid out in five levels of climate change severity:

I: Small but statically-significant shifts away from the reference climate;

II: Palpable changes in the frequency-intensity-duration of climate events that begin to surpass informal and formal socio-technical thresholds like flood plain demarcations;

III: Extreme climate episodes rare in the past become typical; emergence of new types of extreme climate episodes or syndromes;

IV: New climate epochs: Large-scale discontinuities and permanent change in regional climates;

V: Catastrophic climate change.

Initially, a severe climate change early detection and warning system should be poised to detect the higher-level threats, III, IV and V, that take the climate into new domains of impact, while counting on the extant warnings systems to attend to less extreme climate variations. Indeed, it may well make sense to work at first to anticipate only the "truly catastrophic events" that far out-strip social resiliency (Tierney 2009, p. 1). Presumably this would include the larger magnitudes events like those laid out by Shellehuber at al., and Lenton et al., such as a flip in the Atlantic thermo-haline current (THC) or rapid deglaciation of Greenland. Such events might also evoke attempts to intervene physically with geo-engineering.

The population of dangerous climate thresholds and potential tipping elements (and their relevant tipping points and regional or global climate outcomes) is not yet clearly discerned, though roughly a dozen threats have emerged in the literature (Lenton et al. 2008) and some half dozen have been treated to very rudimentary probability assessment (an expert elicitation from 52 experts conducted by Kriegler et al. 2009; see also Arnell et al., 2005). Lenton et al (2007) offer a "burning embers" depiction of eight tipping elements, relating the likelihood of tipping to increased GMT. But, as pointed out before, we do not have a credible source for probabilities of achieving those GMT increases (warming projections are still offered as a range of scenarios subject to change due to GHG mitigation, rather than a best guess or prediction *per se*; see: Morgan and Keith 1998, and recent concentration scenarios in Moss et al., 2010). To get to an early warning system we would need a probability of each change and a set of regional climate conditions that would result. Parry et al.'s (2008) modified "Key Effects" graphics have moved closer to something resembling a warning. GMT is translated into more specific global and regional climate changes, and into effects on natural and social systems, the sort of detail that will emerge from improved climate science. By linking such likelihoods to estimates of impacts we would come closer to risk assessment, and to casting the initial set of tipping elements into something of a climate change Torino Scale.

8.2 Warning Lead Time

Characteristic climate change time frames may be the greatest challenge to a warning system, though some experience with multi-year and even multi-decade warning is accruing in the various geological warning systems in place, and by application of the Torino asteroid scale. Several time elements are at play in severe climate change that might stem from global warming: when would GHG loading cause certain climate effects? At what lead time might reliable predictions be available? How fast or slow would those effects manifest themselves in factors of concern to society, like extreme droughts, excessive heat, or rapid sea level rise?

The critical question in terms of early detection and warning is just how accurately, and at what lead time, could we anticipate severe climate shifts (Scheffer et al. 2009). The challenge is to translate what Lenton et al. termed the "policy-relevant" time horizon into necessary lead times and certainties for adaptation or intervention decision-making (further examined below).

8.3 Location

The geographical focus of forecasts and warnings must be carefully specified to be useful. Due to an understandable wish among forecasters to avoid false negatives, most extant schemes systematically over-warn. The provision of regional scenarios in AR4, as reflected in the regional Key Impacts charts, is a step toward localized forecasts and warnings; but the big advance in resolution and down-scaling needed for useful climate change warnings is yet to come. Much more focused monitoring is needed, of specific ice sheets, ocean currents, and other discreet climate elements of concern, especially those that might exhibit threshold behavior (Scheffer et al. 2009; Lenton et al. 2009). Some of the tipping elements identified by Lenton et al. have something of a defined geographical footprint, but most need much more research to pin down the teleconnections that would allow useful warnings for particular regions.

8.4 Skill, Usefulness and Decision-Making

In decision-analytic terms, the skill and lead time of predictions, the temporal and spatial profile of the event, and the nature of potential responses all interact to define a useful warnings-response space. The challenge here is to extend the analysis of short-term and seasonal forecast usefulness (Katz and Murphy 1997; Stern and Easterling 1999) to climate change *per se*.

In this effort it is prudent to keep in mind lessons from the early forecast value studies: Thompson (1963) warned that much depends on the decision-maker's sensitivity to downside loss, especially if a loss effectively knocks them out; Murphy (1994) cautioned that forecast pay-off studies focus on marginal costs and losses in repetitive forecasts and decisions, and may not extend to unique and high-risk situations. That is, the simple cost-loss model effectively applied to routine weather forecasts and warnings since Thompson's work in the 1950s and 1960s may be ill-suited to radical climate change (Katz and Murphy 1997). Still, the original formulation by Thompson of "protect" vs. "don't protect" based on a forecast of adverse weather (rain, frost, etc.) is not categorically different from the situation that decision-makers would face with a warning of severe climate change, as well as the "Go / No-Go" frame that might apply to some geo-engineering technologies, though the probability and uncertainty values would have to be derived from Bayesian statistical and other approaches (Schneider 2001; Pittock et al. 2001), perhaps including expert elicitation (Morgan and Keith 1998; Arnell et al., 2005), rather than empirical frequencies and skill scores. One early study, on the decision to seed hurricanes (Howard et al. 1972), somewhat bridges the decision realms of weather forecasts and climate warnings, and presages some of the conundrums of geo-engineering decision-making, like deciding when to act base don forecasts, detecting and valuing the geo-engineering effect, and dealing with the potential argument that once a climate intervention has begun, then all subsequent climate fluctuations and their damages are "owned" by the intervening authority.

The problem of critical and costly decisions made on the basis of uncertain warnings is most well-researched for hurricane evacuation planning (Baker 2000; Letson et al. 2007; Gladwin et al. 2009; Lazo et al. 2010), and certainly such inevitable trade-offs among warning lead time and accuracy, and individual and collective decision-making, will apply to severe and/or abrupt climate change, and, as with hurricane evacuations, is exacerbated as cost of adaptive responses, and time needed to implement them, increase. Climate change warnings, even for "abrupt" changes, will operate in longer time-frames than weather forecasts and warnings, presumably allowing more opportunity for adaptations to be adjusted as conditions evolve (as opposed to the nerve wracking go/no-go decision in hurricane evacuations). Climate change warnings that might evoke, for example, stockpiling of food and fuel supplies, are in a different decision-class than those that might logically lead to abandonment of coastal settlement.

Lead-time is further complicated by the intricate conceptual structure of climate tipping points. A qualitative change in some crucial feature of the earth's climate is set in train by a control variable exceeding a critical value (Lenton et al. 2008). That tipping point may precede manifestations relevant to society (e.g., damaging sea level rise) by quite a long period of time, and the crucial change (ice sheet disintegration) would proceed in some transition profile that could be more or less abrupt. Lenton et al., assessing tipping elements associated with anthropogenic global warming (AGW), defined a policy time horizon ($\boldsymbol{T}_{\mathrm{p}}$) as the condition in which the control and its critical value are identifiable, and the critical value can be accessed by AGW in the time frame over which policy might mitigate anthropogenic forcing. But here I wish to apply time-frames of early warning and response, and thus elaborate $\boldsymbol{T}_{\mathrm{p}}$ into different decision frames, in this order:

$\boldsymbol{T}_{\mathrm{p}\boldsymbol{m}}$ (mitigation): the time needed to modify GHG emissions (half-centuries to decades) to avoid reaching a tipping value;

$\boldsymbol{T}_{\mathrm{p}a}$ (adaptation): the time needed to prepare for (adapt to) the coming change, e.g., raising sea walls, shifting agricultural zones, or retreating from the coast (decades to years);

$\boldsymbol{T}_{\mathrm{p}\boldsymbol{i}}$ (intervention): the time needed to deploy geo-engineering technologies and for them to take effect (years to months).

Of course the decisions associated with these lead times could interact; climate shifts that would entail very large adaptation costs might evoke a decision to try intervention, especially if those costs could not be spread out over a long lead time (Table 1). As Smith et al. (2011) argued, “the decision lifetime interacts with the nature of the climate change elements to which the decision is sensitive, as to whether these are changing rapidly or slowly, and with certainty or not.” (p. 199). Given the likelihood that climate change forecasts will remain of low skill, indeed, that some tipping elements would offer pre-cursory lead time and some would not, it might help to conceive $\boldsymbol{T}_{\mathrm{p}a}$ as including both prediction lead time (say starting when the forecast can be considered to have achieved half of the theoretically obtainable skill) and the transition time of the climate change (say halfway to complete state change, i.e., tipping half-life) (Table 2).

The prediction or transition time could also be conceived as including a period after the tipping value is passed but before any significant climate changes are monitored, or impacts accrue. Altogether, this might be referred to as $\boldsymbol{T}_{\mathrm{p}r}$: the time available (or needed) to respond in various ways as pre-cursory warnings evolve, or the time allowed for ramping up responses as the change is actually manifest in some time-magnitude profile (Table 2). $\boldsymbol{T}_{\mathrm{p}i}$ is a sub-set of this value, but is even more conditioned by the nature of the intervention: some geo-engineering technologies might be suited to implementation on evidence that AGW is approaching a critical value (go-on-warning), while others might be delayed until somewhere along the tipping profile (go-on-detection). Such decisions would be sensitive to the scale and reversibility of the climate change and of the intervention: proposed geo-engineering technologies differ in terms of their bi-variate (go/no-go) structure, on-off vs. titration capabilities, geographical scale, and speed of implementation and traction (Royal Society 2009; MacCracken 2009).

Like the emergency manager forced to initiate a coastal evacuation at rather low probabilities of a hurricane strike because of the large population to be moved, some geo-engineering interventions would, in theory, be most effective early in a climate emergency (under low certainty of threat, perhaps after the tipping threshold but before any palpable climate effects) while others could be effectively implemented and titrated as the change is manifest and detected. The down-side risk aversion (i.e., losses associated with not responding to a change that eventually causes severe disruption) found in value-of-forecast studies is perhaps somewhat balanced in the geo-engineering case by aversion to the assumption of responsibility for the totality of climate variation following intervention (and even following the cessation of intervention; see Ross and Mathews 2009).

Overall, one can hope that **Tp*r*** associated with likely tipping elements is *sufficient*; that is, that severe and abrupt changes requiring the most draconian and time-consuming adaptations, or requiring geo-engineering intervention, will happen to be those that exhibit the longest premonitory time before the onset of damaging conditions; if we are unlucky, the events that offer the shortest premonitory windows will turn out to be those for which longer periods of preparation would be needed. The state of science on thresholds, feedbacks, and tipping points in the earth's climate precludes pinning down, right now, the distribution of possibilities, but does suggest, to my reading at least, that several different flavors of thresholds might emerge, including some with useful precursors and others without (see, for example, Scheffer et al. 2009). Lead time at a given level of skill would probably lengthen with a longer record of the system (better monitoring could help) and, of course, with the strength of the premonitory indicator (e.g., slowing down, flickering, or increase serial auto-correlation, as described in Scheffer et al. 2009). But the decision-maker is still faced with the trade-off between type I and II errors in a warn-on-prediction vs. warn-on-detection approach. Uncertainty adheres to the social response as well; we may be able to retreat from the shoreline faster and with less socio-economic disruption than past experience of rather sluggish land use adjustment to natural hazards suggests (Travis 2010), or we might not be able to agree on a geo-engineering response in the time allotted.

6. Next Steps

The premise of this paper is that a climate change detection and early warning system is, in effect, emerging, but with little plan or design. Prospects for effective social adaptation and for geo-engineering intervention can be improved by skillful early warning, especially for severe, abrupt climate changes. Experience with current natural hazard warning systems indicates that their effectiveness is not determined simply by the accuracy of the prediction; many other factors play into warnings usefulness, especially lead time and the available response set. Without some care, the emerging *ad hoc* system may not easily be molded into effective climate change early warnings if and when the capability and need arises.

Steps toward climate change warnings would include more effort to census and profile the discrete climate events that should be the focus of early detection and warning, to develop the links between climate events and socially-relevant impacts, and to enlarge and assess the effectiveness of potential responses. Warnings experience tells us that system design must be guided not only by skills at predicting the "what," "when" and 'where", but also by the needs of the users: if aimed, for example, at teams of geo-engineers waiting for the green light, then the system must be sensitive to the geo-engineering scheme's implementation and governance structure (American Meteorological Society 2009; The Royal Society 2009), including requirements for lead time, specificity, and quantification of uncertainty. We need careful thought on the form of warnings. The climate change community could right now usefully emulate the process whereby astronomers came up with the Torino Scale. It is too early to start issuing warnings of severe climate change, but not too early to sort out how the threat might be evaluated and communicated as knowledge improves or, worse, if pre-monitory signs begin to appear.

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FIG. 1. Extant early warning schemes analogous in many ways to the challenges of severe climate change warnings: (a) The Torino Scale for asteroids is meant to be up-dated over years and decades as new data become available. Available at: http://impact.arc.nasa.gov/torino.cfm

(b) The Volcano Unrest Warning scheme, in place for the Long Valley Caldera in California as described in section 3.0, and modeled after similar warning schemes around the world. Available at: http://volcanoes.usgs.gov/activity/alertsystem/icons.php

THE TORINO SCALE

Assessing Asteroid/Comet Impact Predictions

No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

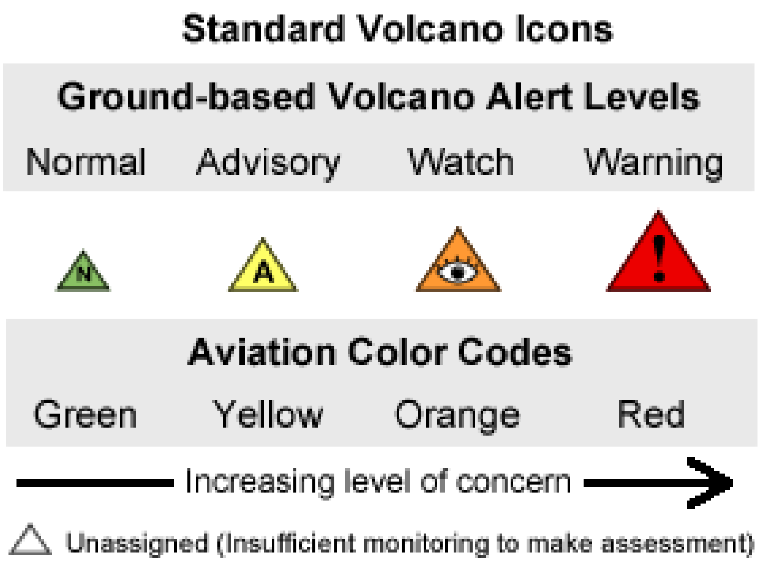


Figure 2: "Reasons for Concern" graphic as depicted for the IPCC Third Assessment Report (left0 and proposed for Assessment Report Four (right). From: Smith et al., 2009.

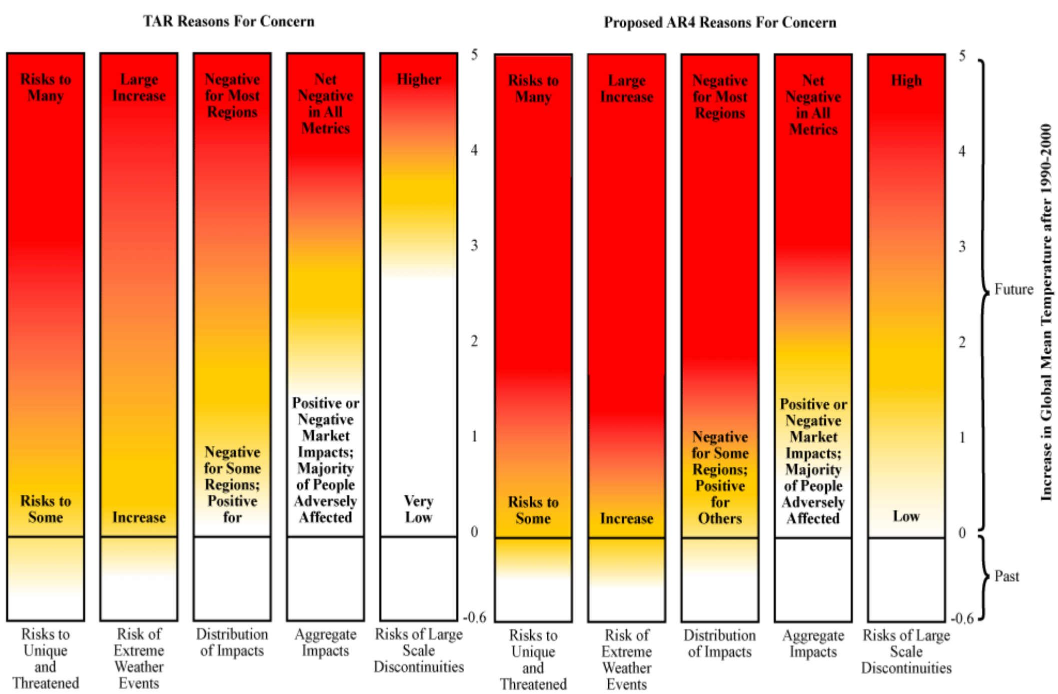
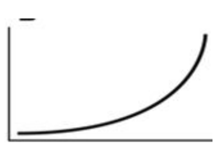
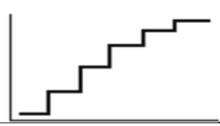
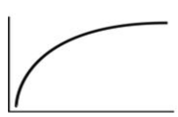


TABLE 1. Lead time and costs of potentially necessary adaptations might bias society toward certain types of policy responses.

	Long Lead Time	Short Lead Time
Large Adaptation Costs	Mitigate	Geo-engineering Intervention
Small Adaptation Costs	Adapt	Adapt (then perhaps intervene after tipping)

Table 2: In addition to forecast lead time, the climate change or flip itself might offer some ramp-up time for responses (adaptation or intervention). If we are averse to intervention, then some tipping profiles might be interpreted as allowing the "Go" decision for adaptation or intervention to be delayed until monitoring has detected and characterized the threat ("go on detection"). But given theoretical reasons to expect a rapid transition, then the decision to act may be pressed to rely on forecasts of even relatively low skill ("go on prediction").

	High Forecast Skill	Low Forecast Skill
Slow Start 	***Act on Detection***	***Act on Detection***
Step Transition 	***Act on Forecast***	***Act on Detection***
Rapid Start 	***Act on Forecast***	**? Act on Forecast**