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Going to extremes: propositions on the social response to severe climate change

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Abstract The growing literature on potentially-dangerous climate change is examined and research on human response to natural hazards is analyzed to develop propositions on social response pathways likely to emerge in the face of increasingly severe climate change. A typology of climate change severity is proposed and the potential for mal-adaptive responses examined. Elements of a warning system for severe climate change are briefly considered.

1 Introduction

This article derives its inspiration from Tebaldi et al. (2006), and from the papers gathered in *Avoiding Dangerous Climate Change*, proceedings of the Exeter, UK, conference by the same name (Schellnhuber et al. 2006). These publications bracket two regimes of climate extremes that could obtain in a cumulatively warming world: palpable changes in the frequency and intensity of events that are recognizable expressions of a climate that, while changing, is not categorically different from the recent climate (Tebaldi et al. 2006), and climate excursions that pose novel conditions deriving from large-scale discontinuities as the climate is forced beyond bio-physical system thresholds into a new state (Schellnhuber et al. 2006).

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Ways of conceptualizing and analyzing potentially-extreme climate change are in flux, and a partial re-framing of the global warming problem as posing extraordinary risks of irreversible and abrupt climate change has been underway for a few years (e.g., CCSP 2008a; Schneider et al. 2000; Schneider 2004). The reframing accelerated with the Exeter Conference, and quickened in wake of the Intergovernmental Panel on Climate Change's (IPCC) fourth assessment report, AR4 (Risbey 2008). This article attends to the small chance that human activity will sufficiently alter the global climate over the next several decades, even as the international community seeks to reduce human forcing functions, such that severe climate change occurs. It first briefly examines the logic of attending to low probability but high consequence changes, offers a propositional inventory of potential social response to extreme climate change drawn from the literature on natural hazards, and then develops a typology of climate change severity. The paper concludes by examining the potential for maladaptive responses to extreme climate change and the nature of a severe climate change warning system.

2 Going to extremes?

The potential for extreme climate change is receiving greater attention in scientific and popular discourse. One driving force, the United Nations Framework Convention on Climate Change (UNFCCC) Article 2, evoked efforts to define a threshold of "dangerous" anthropogenic climate change associated with the increase atmospheric concentrations of greenhouse gases (GHG). Such a threshold has the positive quality that it can act as a GHG mitigation target. Much of the research attention in this vein is on identifying the actual geophysical processes and events that represent *prima facie* dangerous climate change (Schellnhuber et al. 2006; see also Arnell et al. 2005: who offer a typology of potential abrupt-climate-change events). The list includes dramatic scenarios such as disintegration of the West Antarctic or Greenland ice sheets, disruption of North Atlantic meridional overturning or thermohaline circulation (MOC/THC), degradation of the Amazonian carbon cycle, and rapid acceleration of GHG releases from other sources (see also CCSP 2008a). Given this focus, analysts also tend to think in terms of "abrupt" climate change (Committee on Abrupt Climate Change 2002). Any of these processes, set in train at some threshold of climate forcing, would likely yield a range of extreme climate effects regionally or globally.

Here I wish to explore not the threshold between safe and dangerous climate change, nor the types of bio-geo-physical thresholds or events that could cause (or, in themselves represent) abrupt and/or severe climate change (as nicely done by Arnell et al. 2005, and at the Exeter Conference), but rather the thresholds and pathways of potential social responses to prima facie severe or even catastrophic, climate change. Only a few researchers have examined the notion from the perspective of social vulnerability and risk. Schneider and Lane (2006; see also Dessai et al. 2004, p. 13), in addressing "dangerous" climate change, differentiate bio-physical and socio-economic thresholds, and note that any logical notion of dangerous change must relate to key vulnerabilities that include both the physical dimensions of change (magnitude, timing, persistence, etc.) and the sensitivity, importance, and potential for adaptation in the ecological and/or social systems at risk (summarized in

Schneider et al. 2007, Chapter 19 of the IPCC's AR4 Working Group II report). They also lay out a risk assessment approach to thinking about extreme climate change (Schneider and Lane 2006, pp. 16–17). Yamin et al. (2006) examine ways to assess and establish social impact danger thresholds (that could eventually be breached even by smooth, linear change) that can act as policy target values.

Yet the climate impact and adaptation studies field has an awkward relationship with extreme or severe climate change. There is much logic in focusing on scenarios less extreme than many of those addressed at the Exeter Conference; extrapolated versions of the current climate are more likely than abrupt, extreme climate change, and thus appear to provide a firmer basis for projecting impacts. The climate impacts community is also wary of focusing on abrupt, dramatic events, either because such discontinuities did not appear early on as useful analogs to what was expected to be a smoother, cumulative change in the global climate, or, more recently because in the quite-politicized debate over mitigation of global warming, advocates who cite extremes have been accused of exaggerating the threat to push policy change. Hulme (2006) argued in a British Broadcasting Corporation (BBC) opinion essay that the Exeter Conference abetted the unscientific hype by proponents of GHG emission reductions who use what he called scare stories of "climate chaos". Hulme reckoned that use of terms like irreversible, rapid and catastrophic could be counterproductive, concluding that "the language of catastrophe is not the language of science." Perception studies do indeed reveal the existence of an alarmist camp in the global warming debate, or what Leiserowitz (2007) termed an alarmist "interpretive community," but Risbey (2008), in an analysis of climate change discourse after Exeter (and after Hulme's BBC opinion article), concludes that the emergence of greater attention to and discussion of extreme change represents scientists' authentic alarm about potentialities rather than an alarmist strategy.

The Exeter Conference authors do not fit into the "climate chaos" camp. The papers presented there (as made available in Schellnhuber et al. 2006), offered a careful assessment of the scientific basis for concern about abrupt shifts in the climate system, and physical science attention to such shifts is now well established (Committee on Abrupt Climate Change 2002). The few social science and policy-oriented papers in the volume (e.g., Yamin et al. 2006) are quite cautious and measured. Global warming with a strong anthropogenic signal has become paradigm not because of scare stories but through the dogged persistence of global warming research and assessment, the vast bulk of which has focused not on extremes and potential climate catastrophes but on changes in average conditions and likely outcomes that accumulate over decades and centuries. Indeed, some analysts feel that the climate change and impacts literature is too conservative, and overly focused on likely scenarios to the exclusion of more extreme outcomes that cannot be scientifically precluded as global warming proceeds. Hansen (2007) has argued, in both the technical literature and in public policy venues (Kerr 2007), that the IPCC process reflects this conservatism, and that it has yielded, for example, underestimates of current and future rates of sea level rise (see also Oppenheimer et al. 2007).

Several of the papers from the Exeter Conference (see especially the exhaustive literature review by Warren 2006) note the lack of attention to extreme events and abrupt change in the broader impacts and adaptation literature, and Arnell et al. (2005) conclude: "Virtually all research into adaptation to future climate change has focused on 'conventional' gradual climate change..." (p. 52; see also Liverman 2008).

A battle over discourse (Risbey 2008) should not obscure the logic of giving appropriate attention to low probability outcomes in keeping with well-developed principles, and long-standing best-practices, of risk assessment and hazards analysis (as applied, for instance, by Schneider and Lane 2006). As Hulme argues, extremes should not be used purposefully to elevate people's fears so that mitigation becomes more likely. Rather, the impacts community should give due attention to the potential for extreme outcomes.

But what is due attention? IPCC WGII at least conceptually encompassed severe and extreme climate change in AR4 by casting some of its findings in a risk assessment framework (in Chapter 2, Carter et al. 2007; and chapter 19, Schneider et al. 2007). Figure 2.1 in Carter et al. (2007, pp. 142–143) allows for "extreme outcomes," which are termed "low probability" and "least likely," and applies the notion of "coping range," outside of which, presumably, severe consequences obtain. IPCC's science assessment team (Working Group I) rather gently raises concerns about extreme climate change by concluding that warming above its "likely" range "cannot be excluded" (Meehl et al. 2007: 749). Depending on how one decodes AR4's probabilistic language and statements of uncertainty, WG I implicitly allow up to a 17% chance that climate sensitivity (the global average equilibrium warming associated with a GHG doubling) is greater than 4.5°C. That is, the area of the distribution outside of WG I's "likely" (or 66% probability) range, between 2.5°C and 4.5°C, divided in two and assigned equally to either tail, indicates a roughly one in six chance of warming greater than 4.5°C (Schneider 2009, p. 1104). They also state that warming is "Very Unlikely" to be less than 1.5°C, suggesting that the distribution may be negatively skewed (as suggested in Kerr 2007; see also Roe and Baker 2007 on the potential for larger warming). Warren's (2006) exhaustive review of the impacts literature, conveniently organized by "global average temperature rise above pre-industrial," provides little doubt that the regime above 4.5°C can reasonably be labeled severe or dangerous. Since AR4 some analysts have suggested that we should be prepared to adapt to much greater warming (Parry et al. 2009). So, the scientific consensus would appear to posit a non-trivial risk of very extreme conditions and impacts in the next century. In keeping with this notion, the remainder of this paper employs the potential for severe climate change, including its catastrophic tails, not as an argument for greater GHG mitigation, but as a risk needing attention, and the raison d'etre for examining social responses to natural extremes more generally, in order to extrapolate to severe climate change.

3 Social response propositions from hazards research

Framing the global warming problem as potentially yielding "unconventional" climate change, including abrupt on-set of severe climate conditions, points to a body of work from which we might gain some diagnostic and prognostic insight into human response: research on natural hazards. The hazards literature has been called on before to illuminate possible social response to global warming (Burton 1996; Kates et al. 1985; NAS 1992), mostly in an exercise of "reasoning from extremes:" using lessons from disasters to illuminate likely responses to less abrupt, more moderate climate trends. Here I turn to natural hazards as a logical analog to severe climate change itself.

The analog to hazards is obvious but also imperfect. Hazards affect relatively small areas; they do not test the global response capacity as extreme climate change might. And hazard responses in the past occurred, by definition, under assumptions of stationarity: hazards were seen as tails of a stable distribution of geo-physical conditions, not as manifestations of fundamental change in those conditions. The response pathway to the storm surge hazard may be different from that to rapid sea level rise. On the other hand, hazard responses evolved as the nature of the threat at any location was realized over time, and several climate impact analysts have suggested that capacity to deal with future climate change is related to capacity to cope with current climate variability (Arnell et al. 2005, p. 50). So, I attempt to distill from the research on natural hazards and disasters a set of general response pathways. This is similar to how Kates et al. (2006) drew on hazards research to analyze the likely path of recovery following Hurricane Katrina. I attend almost exclusively to the US hazards policy history, which has been critically assessed occasionally for over half a century (beginning with White 1945) and, fortunately, has now been treated to two comprehensive reviews (Mileti 1999; White and Haas 1975), as well as several other multi-hazards evaluations (e.g., Cutter 2001; Kates et al. 2006; Platt 1999).

Hazards analysis reveals half a dozen reaction modes that could denote key pathways of human response to worsening climate extremes:

1. *Technological control and intervention* of the physical phenomena themselves.
2. *Physical protection and barriers* to make places safe from the hazard.
3. *Monitoring*, *forecast*, *and warning systems* to provide some sense of certainty and safety and to guide other responses like evacuation.
4. *Building codes and engineering design standards* to reduce damages of given events;
5. *Relief and insurance* mechanisms to spread the burden and to support recovery and reconstruction.
6. *Land use changes* to reduce underlying exposure and vulnerability.

3.1 Technological control and intervention

Efforts to control hazard phenomena themselves date back to the dawn of human history, and range from prayer to sacrifice to cloud seeding. In recent times, schemes as unlikely as bombs to disrupt tornadoes and as grandiose as a dam across the Bering Straits and continental scale water transfer systems (in western North American and the former Soviet Union, for example), have been seriously considered (Kellogg and Schneider 1974). Some (not very serious) thought was given to lubricating earthquakes faults to release strain incrementally (http://earthquake.usgs.gov/learning/faq.php?categoryID=6). A vast array of pseudo-scientific and scientific methods for modifying the weather (everything from rain to hail to hurricanes) has been proposed and tested in the field, and even applied operationally (though with poorly-assessed effectiveness). Some control-of-nature projects have yielded marked changes in ecological systems, though often with unintended consequences: a system of wildfire suppression in the US has been operated by federal, state and local agencies since just after World War II, and has, indeed, altered fire regimes (Pyne 1997). Some geo-engineering schemes are designed to mitigate past impacts: a promising, remedial "re-engineering" of the Florida Everglades is underway (Babbitt 2005, pp. 13–54).

Of these, there seems little doubt that *purposeful weather and climate modification* would expand in the face of significant climate change. Indeed, a campaign is currently underway to re-assert weather modification into the realm of acceptable, scientific resources management. Federal funding for both research and applications was cut in the late-1970s, but a dedicated cadre of serious-minded atmospheric scientists have continued to pursue the technology and have managed to practice seeding under state and private programs across the nation (in, for example, Texas, Utah, several Great Plains states, Illinois, Colorado and California). Their continued advocacy led to recent draft legislation in the US Congress (The Weather Modification Research and Technology Act), and to a National Research Council (NRC) assessment of the scientific basis for weather modification. The NRC study recognizes the attraction of weather modification, but questions its effectiveness and usefulness without significant further research investment especially in understanding cloud and precipitation processes (NRC 2003). The NRC report evoked a rejoinder from the Weather Modification Association (Bow et al. 2004), and one cannot help but be impressed with the quite optimistic assessment of purposeful weather modification conveyed in that response, and the credence given to purposeful modification in an earlier assessment by Cotton and Pielke (1995), two veterans of both research and operational cloud seeding.

The common thread running through weather modification that keeps it alive is the simple fact that it is cheap and, in theory, yields substantial benefits with even modest effects, especially applied to extremes of weather and climate. Leaders of Project Stormfury, the federal program to modify hurricanes:

> ...estimated that if during the next ten years the amount of money spent on hurricane modification continued at the same annual rate ($1 million), and if ... one severe hurricane such as Camille in 1969 or Betsy in 1965 would be weakened so that its damage was reduced by 10 percent, then the potential benefit/cost ratio would be roughly 10:1 (Sorkin 1982, p. 95).

Yet, hazards assessments have generally concluded that weather modification is not a viable tool for hazard reduction. White and Haas (1975, pp. 383–384) allowed that it might prove useful in future with further scientific advances (anticipating the NRC assessment), but the next major hazards assessment (Mileti 1999) essentially ignored it as a hazards mitigation tool, even for droughts. Its social acceptability remains in doubt: nearby cloud seeding was inaccurately linked to the Rapid City flash flood in 1972, and weather modification evokes a host of social and environmental concerns (Steinberg 2000, pp. 140–145). But a look back through the quite large gray and peer-reviewed literature on weather modification, its impacts, and its potential (Cotton and Pielke 1995), suggests that it will re-emerge in the face of extreme climate change.

3.2 Physical protection and barriers

The first critical assessments of hazard response in the US (White 1945) cautioned that the rush to build dams and levees to protect the nation from floods brought with it a series of unintended consequences, including the pathology termed the “levee effect” whereby protection encourages development and thus makes future, inevitable failures, more damaging (see also Burton et al. 1968, and Platt 1999). Penning-Rowsell et al. (2006) found the same historical pathway of response to floods in Britain: protection rather than relocation, with each major flood causing “policy acceleration” further down the physical protection path. In the US, physical barriers remain a preferred tool for reducing flood and storm-surge impacts, despite continuing concerns that protective works provide a false sense of security and even in the face of new risk assessment approaches that make the potential for failure more explicit (Mileti 1999, p. 203; Platt 1999) and the many post-Katrina evaluations that raised questions about the New Orleans hurricane protection system and, by inference, similarly designed structures elsewhere (e.g., Hurricane Katrina External Review Panel 2007). Indeed, new flood and surge barriers like the systems arrayed for Providence, RI, and the Thames Estuary have been proposed for southern Louisiana in the aftermath of Hurricane Katrina despite widespread failure of existing works (Van Heerden and Bryan 2006). How these engineering systems would fare in a changing climate remains to be seen. But, the likelihood that climate change will evoke more investment in physical barriers suggests more attention to the “levee effect” and greater efforts to make often subtle and complex risk analyses more accessible to decision-makers.

3.3 Monitoring, forecast, and warning systems

It is not surprising that science would attempt to deliver hazard forecasts, especially where science and engineering cannot control the phenomena nor make society much less vulnerable, but can relatively cheaply observe and predict (with varying skill) the geophysical events. Warning systems are in place for everything from earthquakes to tsunami to winter storms, and policy assessments have generally found them effective and worthwhile (Mileti 1999; White and Haas 1975). The US hurricane forecast and warning system is clearly useful, and improving (Willoughby et al. 2007). As property and people at risk on the hurricane-prone coasts increase, the social system becomes more reliant on forecasts and warnings (e.g., successful hurricane evacuation depends on reliable landfall forecasts rather than, say, land use limits along coasts).

Still, forecasts and warning systems have struggled with limits on their efficaciousness likely to hold in their application to severe climate change: how to get the message to the target audience, how to avoid over-warning, and how to elicit the correct response (Mileti 1999; Sorensen 2000). And the many unanswered questions about the usefulness of seasonal climate forecasts raised by Stern and Easterling (1999, pp. 129–141) presage great uncertainty about the usefulness of climate change forecasts and warnings. Nevertheless, seasonal climate forecasts are likely to be extended to, and additional monitoring and modeling applied to, abrupt climate change (Arnell et al. 2005; Committee on Abrupt Climate Change 2002; and briefly discussed at the conclusion of this article). The challenge, as with all other forecast and warning systems, will be to carefully design each stage of the climate change warning system (monitoring, risk assessment, warning formulation, dissemination, and application), applying the many lessons learned from other warning systems (see, for example, Basher 2006).

3.4 Building codes and engineering design standards

Building codes for hazard loss reduction have been widely accepted and demonstrably effective; they made a difference in Hurricane Andrew and an even bigger difference by the active 2004 hurricane season in Florida because they had been further strengthened (Insurance Information Institute 2007). Both comprehensive US hazards policy assessments (Mileti 1999; White and Haas 1975) cited building code changes as an especially effective hazard mitigation tool across almost all hazards, one enduring bright spot in hazard loss reduction. An effective system of code development, testing, and application is in place, with some weaknesses noted in enforcement (Mileti 1999, pp. 164–166). Elaborated building codes would certainly be part of adaptation to extreme climate change, including for: wind, rain-shedding, drainage, soil stability, snow loading, and heating and cooling. This is one area where the hazards experience points to good potential for adaptive response.

3.5 Relief and insurance

Loss sharing and spreading mechanisms (private and government insurance and relief) are applied to all sorts of hazards and disasters (including drought as early as 1936, and most natural hazards starting in the 1960s; White and Hass 1975). Insurance and government aid remain a big part of drought adaptation in the US, both as part of agricultural policy and legislation in response to specific droughts (Riebsame et al. 1991). Insurance theory is well understood and applied by the private sector, less efficiently employed by government, and often misunderstood by policy-holders and non-adopters (Kunreuther and Michel-Kerjan 2007). Nevertheless, insurance is key to coping with hazards, and development would be severely constrained in some areas without it. Disaster relief (the provision of special resources to those affected by natural hazards) plays a similar, though patchy, role in hazard response. Some analysts have suggested that relief is mal-adaptive, bailing out risky development and rewarding poor planning, especially in floodplains (Platt 1999). Mileti (1999) concludes that expectations of relief do not necessarily encourage hazard zone occupance, but insurance might. The leading scholar of hazards insurance, Howard Kunreuther (2006), concluded after Hurricane Katrina that expectations of government aid reduced adoption of both pre-hazard mitigation and insurance.

Relief and insurance will continue to be an important adjustment to all sorts of hazards, but it is difficult to judge how they would operate in the face of severe climate change. Property insurance is absolutely crucial to continued flood plain, coastal, and earthquake zone development, affects the future of entire states (e.g., Florida and California), and is often subsidized by states. But the interplay of pre-hazard mitigation, insurance, and government relief is complex. How might this syndrome play out in a worsening climate? Platt (2007) notes that climate change is "barely mentioned" in a recent evaluation of the National Flood Insurance Program (NFIP). So far the main response in insurance has been to worry that climate change obviates the actuarial basis for efficient insurance coverage, and that more extreme events might out-strip premium pools. Little planning for climate change is yet in place among insurers (Kunreuther and Michel-Kerjan 2007), though the insurance industry has expressed concern about catastrophic potential, and expects that state and federal government will intervene more often to subsidize insurance in order to maintain investment and development in the face of growing losses (Insurance Information Institute 2007).

3.6 Land use change

An enduring finding in hazards research has been that fundamental land use change is rarely part of hazards mitigation. Land use regulation is relatively weak in the US, and attempts to force land use change by law have run into effective social and legal opposition. In a landmark case (Lucas vs. South Carolina Coastal Council; see Platt 1999), the US Supreme Court concluded that the state of South Carolina could not limit coastal development without compensating property owners. Because governments do not have the resources to compensate owners for loss of value of risky land, they have simply forgone land use regulation as part of hazard mitigation. Indeed, market-driven development patterns show little sensitivity to hurricane risks, maybe just the opposite: waterfront property (in, for example, Florida) remains more valuable. These trends were noted in the first national hazards assessments (White 1945; White and Hass 1975; and detailed by Baker and McPhee 1975), and the 1999 assessment concludes that while good ideas for land use management to reduce risks are available, lack of commitment especially by local government (and little support from state and federal levels) continue to hinder their application (Mileti 1999, p. 158). Platt (1999 and 2007) has documented how land use regulation, originally designated by congress as a key hazard reduction tool in the NFIP, was ignored and weakened over time. The result is evident in flood losses. Pielke (2007) and Pielke et al. (2008) have shown that continued coastal development is the main force behind increasing hurricane losses. The current insolvency of the NFIP, partly due to repetitive claims, attests to this enduring trend in inland floodplains as well (Insurance Information Institute 2005, 2007). A similar lack of land use adaptation in earthquake hazards, which are inherently spatial, has also been shown even where California required hazard disclosure as part of real estate transactions (Palm 1981).

3.7 The effectiveness of adaptation

We do not know the effective range of adaptation in the face of extreme climate change, though impacts and adaptation analysts recognize limits to adaptation somewhere between modest and severe climate change (Carter et al. 2007, pp. 142–143; Schneider et al. 2007; Adger et al. 2008). To carry on the analog to natural hazards and disasters, we can anticipate a ramping up of responses over time as the nature of the climate change threat becomes more apparent, and as climate extremes become perceived as linked to global warming. The suite of anticipatory adaptation and preparedness methods (termed mitigation in hazards parlance) prescribed by hazard managers (reviewed above) has been shown to yield large benefits compared to costs. But hazards theory also allows for maladaptation. Several natural hazards researchers have posited a universal "levee effect" or "catastrophe effect" (e.g., Burton et al. 1968; Kates et al. 2006) whereby society's adjustments to less extreme, more frequent events, make social systems likely to experience catastrophic losses from more truly events (e.g., abrupt climate change). The effect, also known as the "safe development paradox," is difficult to measure and demonstrate, but appears to obtain especially in cases of structural flood protection (Burby 2006).

Another way to describe the process that Kates et al. (2006) identify for New Orleans and other reconstruction cases is the tendency for societies to "bounce back" after catastrophes, making things "normal" (or as Kates et al. 2006, put it, to "recreate the familiar") but not necessarily better-adapted. I would argue that such resilience, as opposed to adaptation, has been the hallmark of natural hazard response and policy in the US and elsewhere. Cities are re-constructed, people re-build their homes, and businesses come back, often with government aid. Rarely do underlying land use patterns change. Even the dramatic relocation of some communities after the 1993 Mississippi River floods, in which about 13,000 of the 80–90,000 buildings seriously damaged were moved, pales in comparison to the roughly 10 million residences that lie in the nation's 100-year floodplains; thousands more are constructed each year, often in areas "protected" by dams and levees (Platt 1999, 2007). Lack of land use adaptation points to a major adaptation gap in the face of climate change, especially sea level rise (Nicholls and Tol 2006). If this pattern holds as places face impacts from global warming, then we can expect, at best, a jerky, awkward response to continuously-changing climate. At worst, if hazard-zone occupancy continues to increase, as most researchers expect (see, for example, Pielke 2007, on the hurricane-prone coasts), then we may observe no net adaptation, but rather a worsening of vulnerability and impacts.

The potential for mal-adaptive long-term response pathways is hinted at in AR4. Adger et al. (2007: Box 17.7), raise doubts about the so-called "policy window hypothesis" in which, "immediately following a disaster, the political climate may be conducive to legal, economic and social change which can begin to reduce structural vulnerabilities" (Adger et al. 2007, p. 733). Instead, "the end result is that short-term risk reduction can actually produce greater vulnerability to future events," (p. 733), a re-statement of the catastrophe effect, or what an earlier group of climate impact analysts called the "worsening effect" (Bowden et al. 1981). A key question for impacts research is whether response pathways that emerge as climate change intensifies might worsen or lessen future impacts, and a key element in any adaptation program will be monitoring to track such social trends. As with other hazards, doing so may be aided by a climate change severity scale on which we can organize hypotheses about human responses.

4 The range of climate change severity

Hazard analysts have found it useful to develop categorical scales to provide common benchmarks for assessing impacts and responses to geo-physical events like hurricanes and earthquakes. The complex nature of climate change, which can be defined in purely statistical terms, as events like heat waves, floods, droughts, or even as fundamental change toward what Arnell et al. (2005) called “radically or conceptually different climatic conditions”, recommends a phenomenological typology structured by conditions as experienced by social systems, one anchored on vulnerability thresholds as suggested by Dessai et al. (2004). In that sense, a climate change severity scale would usefully emulate, for example, the Modified Mercalli scale of earthquake intensity based on impacts like human experience of ground motions and damage to structures, rather than the more purely physical intensity scales like the Richter Magnitude scale for earthquakes (based on normalized amplitudes of seismic waves) or the Saffir–Simpson hurricane scale (founded on wind speed and central pressure, but also incorporating damage thresholds in its early incarnations).

4.1 A climate change severity index

A draft typology of climate change severity is offered in Table 1. It is partly inspired by columns II (“Risks from Extreme Climate Events”) and V (“Risk from Future Large-Scale Discontinuities”) of the “Reasons for Concern” diagram in the IPCC’s third assessment report (Smith et al. 2001, p. 958), which was up-dated verbally in AR4’s Synthesis Report (IPCC 2007, pp. 19–20) and graphically up-dated in Smith et al. (2009). Like that diagram, the typology must allow for overlapping and somewhat permeable class limits (as do many other geophysical scales), but the goal here is not to tie the typology to a global warming equivalent, presuming instead that various threshold events, at different warming amounts, could yield regional and/or global climate change of different severities.

The index is anchored both to the current climate (Level 0) and to a hypothetical threshold (between Levels 2 and 3) where social responses would move beyond enlarged and elaborated versions of current adaptations, and into the realm of fundamentally new responses, like mass migrations (e.g., the beginning of strategic retreat from sea-level-rise affected coasts) and deployment of new technologies (e.g., building underground) or traditional technologies at markedly new scales and in novel ways, like sea walls around entire communities and large-scale, long-term weather modification. Level 4 offers “radically or conceptually different climatic conditions” (Arnell et al. 2005, p. 54) the prospect or manifestation of which would elicit desperate geo-engineering attempts. Finally, the scale is anchored at the extreme by climate change that brings about social and ecological collapse.

Further elaboration might yield an index tied to the rate, intensity and character of past climate changes (regional or global), or to deviations from established norms at different rates of, or points in, time (perhaps anchored on 30-, 50- and 100-year thresholds to emulate GHG scenarios). Of course there is some question whether the scale’s Level 0 still exists in the contemporary, warming world. I would argue that in many climate-sensitive sectors and practices, in everything from forestry to the sizing of highway culverts, social systems operate as if the current climate resides in this class (e.g., reflecting perhaps the 1970–2000, or even previous, 30-year norms). Sometimes this assumption is made quite explicit: after the active 2004 and 2005 hurricane seasons in the U.S., and subsequent discussions that global warming might be shifting hurricane frequency and intensity, the director of the National Hurricane Center issued public statements specifically arguing that anthropogenic

Table 1 A climate change severity index

Climate change severity index	Description	Example climate phenomena	Example social responses	Additional population at risk (billions)[a]
Zero	Means and extremes common to the recent (e.g., 30 year) climate	Current means and extremes	Those arrayed (more or less effectively) to absorb current variability	0
One	Small but statically-significant shifts away from the reference climate[b]	Scientific detection of climate change (signal surpassing noise) not necessarily sufficient to elicit social responses	Little to none as first small changes are absorbed by excess capacity and buffer built into socio-technical systems	0
Two	Palpable changes in the frequency-intensity-duration of climate events that begin to surpass informal and formal socio-technical adaptive capacities	Noticeably more frequent, and more intense, climate events (Tebaldi et al. 2006): like the 1988 US drought and 2003 Europe heatwave (Schar et al. 2004; Stott et al. 2004)	Adjustments in regulatory and technical systems such as shifted floodplain boundaries; storm surge evacuation zones; levee and dam enlargement, and changes in insurance systems.	.1 to .5
Three	Extreme climate episodes rare in the past become typical; emergence of new types of extreme climate episodes or syndromes	Atlantic hurricane seasons like 2004/05, and the 2003 and 2005 European heat waves, become "typical" events. Frequent continental "mega-droughts" in North America and Asia (Meehl and Hu 2006) and "exceptional droughts" in China (Shen et al. 2007); sea level rise .2–2 m/century.	Novel interventions (e.g., weather modification; species relocation, and intra-continental water transfers), protection schemes (e.g., sea walls around whole communities); and social responses (e.g., mass migration)	3 each

Four	New climate epochs: Large-scale discontinuities and permanent change in regional climates	THC break down yielding significant cooling in N. Europe (Arnell et al. 2005), enduring "intensified aridity" in SW North America (Seager et al. 2007); sea level rise of 2+ m/century	Geo-engineering attempts to cool the climate and reverse trends like ice sheet melting	6 to maximum future global population ($GloPop_{max}$)
Five	Catastrophic climate change	Run-away greenhouse; Permian-like warm epoch	Social and ecological collapse	$GloPop_{max}$

Each index level can be further described in subscripted terms for important characteristics: e.g., speed of onset (S = slow, over centuries; M = moderate, over decades, and R = rapid, over months to years) and geographical scale (L = local, R = regional, H = hemispheric and G = global)

[a]Following Parry et al. (2001)

[b]For example, at the .05 or .1 level of significance that the relevant distributions are drawn from different populations; that is, from different climate states

global warming was not necessary to explain the swing in hurricane frequency, and that the current surge was best assessed as continuation of the past regime, which alternated between more and less active episodes, not the sign of underlying change (as documented in detail by Mooney 2007, p. 193). Thus, Level 0 would seem strongly rooted in perception and public policy even as Level 2 and perhaps Level 3 climate change has been reported in parts of the world.

4.2 Moving up the severity scale

The great question here, and the point that divides natural hazards from climate change concepts, is the likely and/or appropriate response pathways for an ever-worsening climate as opposed to the episodic extreme expressions of an ostensibly stable climate. Most climate impacts analysts expect that, initially, adaptations deployed for current climate extremes (Level 0) would simply be intensified and/or slightly modified for Levels 1 (mostly autonomously) and 2 (more consciously) climate change; these levels of climate change might even yield benefits in some areas. In many, maybe most, cases for some time to come, decision-makers will be skeptical that they are, indeed, on a changing climate trajectory, and logically will rely on past response sets. Even though the popular media (for example, Gertner 2007) now routinely point to evidence of on-going climate change (e.g., in the Arctic and the American Southwest), and several examples of Level 1 as well as some Level 2 changes are documented in AR4 and national assessments (CCSP 2008b), the key break in adaptation pathways is yet to come: starting perhaps at the upper end of Level 2, as individuals and institutions realize that cumulative, permanent change is underway and that the underlying basis for many traditional adjustments (e.g., levee systems, floodplain zoning, and evacuation planning) is untenable. The NFIP may be in denial (Platt 2007), but eventually we will not be able to identify, regulate for, and build to, a stable "100 year flood".

Eventually as we work up the climate change severity scale, recognition will grow that severe climate change is imminent or even underway. Level 3 change would evoke dramatically enlarged and elaborated versions of current adaptations (e.g., extended, heightened, strengthened seawalls to hold back storm surges on top of a rising sea level), but may also start to evoke technologies like cloud seeding to reduce hurricane intensity or even to obviate regional drought.

The human experience of truly extreme environmental conditions, those that could be termed catastrophic, is naturally (and fortunately) limited. If we did not live on a planet that offers a reasonably stable environment we might not be having this discussion, as both agricultural and industrial society may never have emerged, under, say, a constant barrage of asteroids, little ice ages, or Permian-like hot spells. In that vein, very severe climate change will elicit not only increasingly extreme versions of the response pathways identified above, but a phase change in response repertoire to the extraordinary and unparalleled.

Level 4 climate change would likely eilict new attempts at technological control, perhaps initially not too dissimilar from mega-plans discussed in the past, like moving water across continents, towing icebergs, or seeding hurricanes (Kellogg and Schneider 1974). Eventually large population migrations, extraordinary changes in agriculture and food systems, and dramatic changes in the built environment (perhaps underground, or in large, domed cities) might emerge. Given the anthropogenic cause of global warming, we would also likely attempt to deploy global carbon and/or radiation budget control systems (Crutzen 2006; Schneider 2001; Wigley 2006), or other geo-engineering schemes meant to reduce the earth's heat surplus or to limit or even reverse ice sheet wasting. Such schemes got a serious airing by the National Research Council's Panel on the Policy Implications of Greenhouse Warming (NAS 1992), and have re-emerged in recent literature. Most assessments of the planetary engineering response pathway identify it as too dangerous (especially in terms of unintended consequences), costly, and/or ethically questionable (Jamieson 1996; Robock 2008; and going back all the way to Kellogg and Schneider 1974). Indeed, Schneider (2004) argues that the UNFCCC's Article 2 can be read to apply to purposeful interventions that might make things worse (as well as to inadvertent change) so there may be some brake on the most ambitious schemes. But if climate risks escalate dramatically, and given the lag effects of GHG emission reductions, geo-engineering interventions will become more tempting.

Further extreme climate change (Level 5) eventually threatens the sustainability of human society. This is implicit in the "Reasons for Concern" diagram in IPCC's TAR (Smith et al. 2001, p. 958), but virtually no impacts and adaptation research extends to this realm of climate change (or even much into Level 4 change). An abiding fascination with the "collapse" of past societies (Diamond 2005) and threats to contemporary society by catastrophic threats like asteroids shows up in popular literature (Posner 2006), and the occasional academic assessment (Smil 2008). Worst-case scenarios are deployed more as a persuasive mechanism than as a research tool.

5 A severe climate change warning system

Arnell et al. (2005) conclude that given the profound uncertainty associated with abrupt or extreme climate change (Levels 3+) that: "Monitoring for the onset of abrupt climate change is therefore the most appropriate short-term adaptive action." (p. 53). Calls for improving the global climate monitoring system in the face of worsening climate change have been expressed for some time (Parry 2001). If we end up, over the next couple of decades, on the upper reaches of global warming (due to continued large GHG emissions, larger climate sensitivity, or both), then concerns about Level 3-to-5 climate hazards will become less academic, and may even need to be operationalized into a global climate monitoring and warning system especially designed to watch for thresholds and abrupt changes. It may become necessary to invest in an abrupt climate change monitoring system in the same way that the National Astronautics and Space Administration (NASA) has invested in an asteroid monitoring system.

The climate change severity scale (Table 1) is used here as a relatively simple categorization to explore potential social response pathways. But there is some logic, as earth system science improves, in adding risk assessment and prognostic dimensions to any climate change scale. Eventually we may need to design a climate change warning system. One model is the Torino Scale (http://neo.jpl.nasa.gov/torino_scale.html) for potential asteroid impacts in which the threat level is a product of probability of impact and potential effects (Morrison et al. 2004). The Torino Scale is designed to vary as additional information is collected about a given, threatening asteroid (the threat rating of a particular asteroid might increase or decrease over the course of years, even decades, as more information about its orbit, size and composition become available). The two key indicators (probability of an impact and likely impacts, from regional to global) are arrayed onto a 10-point threat scale meant to evoke increasing response as risk escalates: first to instigate increased monitoring and analysis (e.g., more effort to track and size the object) and, eventually, to invoke actions to try to prevent the impact.

A similar risk situation is likely to hold for many potential large-scale climate discontinuities, which will take years or decades to evolve and might offer premonitory, though uncertain, indications to earth system scientists (if, of course, the necessary monitoring systems are in place). Threat level could be incorporated into the climate change severity scale as predictions improve or as severe climate change actually materializes.

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References

Adger WN, Agrawala S, Mirza MMQ et al (2007) Assessment of adaptation practices, options, constraints and capacity. In: Parry ML, Canziani OF, Palutikof JP et al (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 717–743

Adger WN, Dessai S, Goulden M et al (2008) Are there social limits to adaptation to climate change? Clim Change 93:335–354

Arnell N, Tompkins E, Adger N et al (2005) Vulnerability to abrupt climate change in Europe. Technical Report 34. Tyndall Centre for Climate Change Research, Norwich

Babbitt B (2005) Cities in the wilderness: a new vision of land use in America. Island, Washington

Baker EJ, McPhee JG (1975) Land use management and regulation in hazardous areas: a research assessment. Institute of Behavioral Science, University of Colorado, Boulder

Basher R (2006) Global early warning systems for natural hazards: systematic and people-centred. Phil Trans R Soc 364:2167–2182

Bow B, Bomar G, Cotton WR et al (2004) The weather modification association's response to the national research council's report titled, 'Critical issues in weather modification research'. Weather Modification Association, Fresno. Available http://weathermodification.org/wma_response.htm

Bowden M, Kates R, Kay P et al (1981) The effect of climate fluctuations on human populations: Two hypotheses. In: Farmer M, Ingram M, Wigley T (eds) Climate and history. Cambridge University Press, Cambridge, pp 479–513

Burby R (2006) Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. Ann Am Acad Polit Soc Sci 604:171–191

Burton I (1996) The growth of adaptation capacity: practice and policy. In: Smith JB, Bhatti N, Menzhulin G et al (eds) Adapting to climate change. Springer, New York

Burton I, Kates RW, White GF (1968) The environment as hazard. Oxford University Press, New York

Carter TR, Jones RN, Lu X et al (2007) New assessment methods and the characterisation of future conditions. In: Parry ML, Canziani OF, Palutikof JP et al (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 133–171

CCSP (2008a) Abrupt climate change. A report by the US Climate Change Science Program and the Subcommittee on Global Change Research [Clark PU, Weaver AJ (coordinating lead authors). In: Brook E, Cook ER, Delworth TL et al (eds) (chapter lead authors)]. US Geological Survey, Reston

CCSP (2008b) Weather and climate extremes in a changing climate. In: Karl TR, Meehl GA, Miller CD et al (eds) Regions of focus: North America, Hawaii, Caribbean, and US Pacific Islands. A report by the US Climate Change Science Program and the Subcommittee on Global Change Research. Department of Commerce, NOAA's National Climatic Data Center, Washington, DC

Committee on Abrupt Climate Change (2002) Abrupt climate change: inevitable surprises. National Research Council, Washington

Cotton WR, Pielke RA Sr (1995) Human impacts on weather and climate. Cambridge University Press, Cambridge

Cutter S (2001) American hazardscapes: the regionalization of hazards and disasters. Joseph Henry Press, Washington

Crutzen PJ (2006) Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? Clim Change 77:211–219

Dessai S, Adger WN, Hulme M et al (2004) Defining and experiencing dangerous climate change. Clim Change 64:11–25

Diamond J (2005) Collapse: how societies choose to fail or succeed. Penguin Books, New York

Gertner J (2007) The future is drying up. NY Times Mag 21:68–77, 104, 154–155

Hansen JE (2007) Scientific reticence and sea level rise. Environ Res Lett 2:1–6

Hulme M (2006) Chaotic world of climate truth. BBC News, November 4. Available http://news.bbc.co.uk/2/hi/science/nature/6115644.stm

Hurricane Katrina External Review Panel (2007) The New Orleans hurricane protection system: What went wrong? American Society of Civil Engineers, Reston. Available http://www.asce.org/files/pdf/ERPreport.pdf

Insurance Information Institute (2005) The National Flood Insurance Program (NFIP). New York. Available http://www.iii.org/media/hottopics/insurance/nfip/

Insurance Information Institute (2007) Catastrophes: insurance issues. New York. Available http://www.iii.org/media/hottopics/

IPCC (2007) Summary for policymakers of the synthesis report of the IPCC fourth assessment report. Intergovernmental Panel on Climate Change. Available http://195.70.10.65/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

Jamieson D (1996) Ethics and intentional climate change. Clim Change 33:323–336

Kates RW, Ausubel JH, Berberian M (1985) Climate impact assessment. Wiley, Chichester

Kates RW, Colten CE, Laska S et al (2006) Reconstruction of New Orleans after Hurricane Katrina: a research perspective. P Natl A Sci 103:14653–14660

Kellogg WW, Schneider SH (1974) Climate stabilization: for better or worse? Science 186:1163–1172

Kerr RA (2007) Pushing the scary side of global warming. Science 316:1412–1415

Kunreuther H (2006) Disaster mitigation and insurance: learning from Katrina. Ann Am Acad Polit Soc Sci 604:208–227

Kunreuther H, Michel-Kerjan E (2007) Climate change, insurability, and liability. U Penn Law Rev 155:1795–1842

Leiserowitz A (2007) Communicating the risks of global warming: American risk perceptions, affective images and interpretive communities. In: Moser S, Dilling L (eds) Creating a climate for change: communicating climate change and facilitating social change. Cambridge University Press, Cambridge, pp 44–63

Liverman D (2008) Assessing impacts, adaptation and vulnerability: reflections on the working group II report of the intergovernmental panel on climate change. Global Environ Chang 18:4–7

Meehl GA, Hu A (2006) Megadroughts in the Indian Monsoon region and Southwest North America and a mechanism for associated multidecadal Pacific sea surface temperature anomalies. J Climate 19:1605–1621

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao ZC (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 747–845

Mileti D (1999) Disasters by design: a reassessment of natural hazards in the United States. Joseph Henry Press, Washington

Mooney C (2007) Storm world: hurricanes, politics and the battle over global warming. Harcourt, New York

Morrison D, Chapman CR, Steel D et al (2004) Impacts and the public: communicating the nature of the impact hazard In: Belton MJS, Morgan TH, Samarasinha NH et al (eds) Mitigation of hazardous comets and asteroids. Cambridge University Press, Cambridge

NAS (1992) Policy implications of greenhouse warming: mitigation, adaptation, and the science base. Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering, and Public Policy. National Academy of Sciences, National Academy Press, Washington, DC, pp 433–464
Nicholls RJ, Tol RSJ (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the 21st century. Philos Trans R Soc A 361:1073–1095
NRC (2003) Critical issues in weather modification research. Committee on the Status and Future Directions in US Weather Modification Research and Operations. National Research Council, Washington, DC
Oppenheimer M, O'Neill BC, Webster M et al (2007) The limits of consensus. Science 317:1505–1506
Palm R (1981) Real estate agents and special studies zones disclosure: the response of California home buyers to earthquake hazards information. Natural Hazards Research and Applications Information Center, Monograph No. 32, Institute of Behavioral Science, University of Colorado, Boulder
Parry M (2001) Climate change: where should our research priorities be? Global Environ Chang 11:257–260
Parry ML, Arnell N, McMichael T et al (2001) Millions at risk: defining critical climate change threats and targets. Global Environ Chang 11:181–183
Parry ML, Lowe J, Hanson C (2009) Overshoort, adapt, and recover. Nature 458:1102–1103
Penning-Rowsell E, Johnson C, Tunstall S (2006) 'Signals' from pre-crisis discourse: lessons from UK flooding for global environmental policy change? Global Environ Chang 16:323–339
Pielke RA Jr (2007) Future economic damage from tropical cyclones: sensitivities to societal and climate changes. Philos Trans R Soc A 365:2717–2729
Pielke RA Jr, Gratz J, Landsea CW et al (2008) Normalized hurricane damages in the United States: 1900–2005. Nat Hazards Rev 9:29–42
Platt RH (1999) Disasters and democracy: the politics of extreme natural events. Island, Washington
Platt RH (2007) Comments on the National Flood Insurance Program (NFIP) evaluation final report. Natutal Hazards Observer November:11–12
Posner R (2006) Catastrophe: risk and response. Oxford University Press, New York
Pyne SJ (1997) Fire in America: a cultural history of wildland and rural fire. University of Washington Press, Seattle
Riebsame WE, Changnon SA, Karl TR (1991) Drought and natural resources management in the United States. Westview, Boulder
Risbey JS (2008) The new climate discourse: alarmist or alarming? Global Environ Chang 18:26–37
Robock A (2008) 20 reasons why geoengineering may be a bad idea. Bull Atomic Scientists 64(2):14–18, 59. doi:10.2968/064002006
Roe GH, Baker MB (2007) Why is climate sensitivity so unpredictable? Science 318:629–632
Schar C, Vidale PL, Luthi D et al (2004) The role of increasing temperature variability in European summer heatwaves. Nature 427:332–336
Schellnhuber HJ, Cramer W, Nakicenovic N et al (2006) Avoiding dangerous climate change. Cambridge University Press, Cambridge
Schneider SH (2001) Earth system engineering and management. Nature 409:417
Schneider SH (2004) Abrupt non-linear climate change, irreversibility and surprise. Global Environ Chang 14:245–258
Schneider SH, Lane J (2006) An overview of 'dangerous' climate change. In: Schellnhuber HJ, Cramer W, Nakicenovic N et al (eds) Avoiding dangerous climate change. Cambridge University Press, Cambridge, pp 7–23
Schneider SH, Kuntz-Duriseti K, Azar C (2000) Costing non-linearities, surprises, and irreversible events. Pac Asian J Energy 10:81–106
Schneider SH, Semenov S, Patwardhan A et al (2007) Assessing key vulnerabilities and the risk from climate change. In: Parry ML, Canziani OF, Palutikof JP et al (eds) Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 779–810
Schneider SH (2009) The worst-case scenario. Nature 458:1104–1105
Seager R, Ting MF, Held IM et al (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316:1181–1184
Shen C, Wang WC, Zhixin Hao Z et al (2007) Exceptional drought events over eastern China during the last five centuries. Clim Change 85:453–471
Smil V (2008) Global catastrophes and trends: the next fifty years. MIT, Cambridge

Smith JB, Schellnhuber HJ, Mirza MMQ (2001) Vulnerability to climate change and reasons for concern: a synthesis. In: McCarthy JJ, Canziana OF, Leary NA et al (eds) Climate change 2001: impacts, adaptation and vulnerability. Contribution of working group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 914–967

Smith JB, Schneider SH, Oppenheimer M et al (2009) Assessing dangerous climate change through an update of the intergovernmental panel on climate change (IPCC) 'reasons for concern.' P Natl A Sci 106:4133–4137

Sorensen JH (2000) Hazard warning systems: review of 20 years of progress. Nat Hazards Rev 1: 119–125

Sorkin AL (1982) Economic aspects of natural hazards. Lexington Books, Lexington

Steinberg T (2000) Acts of God: the unnatural history of natural disaster in America. Oxford University Press, New York

Stern PC, Easterling WE (1999) Making climate forecasts matter. National Academy Press, Washington

Stott PA, Stone DA, Allen MR (2004) Human contribution to the European heatwave of 2003. Nature 432:610–614

Tebaldi C, Hayhow K, Arblaster JM et al (2006) Going to extremes: An intercomparison of model-simulated historical and future changes in extreme events. Clim Change 79:185–211

Van Heerden I, Bryan M (2006) The storm: what went wrong and why during Hurricane Katrina. Viking, New York

Warren R (2006) The impacts of global climate change at different annual mean global temperature increases. In: Schellnhuber HJ, Cramer W, Nakicenovic N et al (eds) Avoiding dangerous climate change. Cambridge University Press, Cambridge, pp 93–131

White GF (1945) Human adjustment to floods: a geographical approach to the flood problems of the United States. University of Chicago Press, Chicago

White GF, Haas JE (1975) Assessment of research on natural hazards. MIT, Cambridge

Wigley TML (2006) A combined mitigation/geoengineering approach to climate stabilization. Science 314:452–454

Willoughby HE, Rappaport EN, Marks FD (2007) Hurricane forecasting: the state of the art. Nat Hazards Rev 7:45–49

Yamin F, Smith JB, Burton I (2006) Perspectives on 'dangerous anthropogenic interference.' Or how to operationalize Article 2 of the UN Framework Convention on Climate Change. In: Schellnhuber HJ, Cramer W, Nakicenovic N et al (eds) Avoiding dangerous climate change. Cambridge University Press, Cambridge, pp 81–91