Extreme Events as Pacemaker of Adaptation to Climate Change[1]

William R. Travis
Department of Geography
and
Center for Science and Technology Policy Research
Cooperative Institute for Research in Environmental Sciences
University of Colorado at Boulder

Introduction

For variety of reasons, extreme events are thought of as propelling adaptation to climate change (Füssel, 2007; IPCC, 2012). In the simplest formulation of this logical assertion, extreme weather and climate events transcend the signal-to-noise threshold and make climate risks starkly evident to decision-makers. Similarly, they make latent societal vulnerability manifest, and overcome economic and political barriers to adaptation. These effects can in theory hold for a stationary climate, whereby extreme events override people's tendency to disregard low probability, and thus infrequent, impacts, especially as time passes without an occurrence. But the signaling effect of extremes is now often invoked for adaptation to a changing climate: an underlying trend in, say, mean temperature, may be difficult for any decision-maker to discern, but more frequent excursions into conditions rare, or even unknown, in the past, become hard to ignore. Framed by a discourse on climate change, an extreme event becomes not just a reminder that climate distributions have tails, but a harbinger of more extremes to come. So extremes are framed descriptively as propelling adaptation and prescriptively as potentially efficient pacemakers of adaptation (Larsen et al., 2008). The title of the IPCC special report, "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" clearly invokes this prescriptive role for extremes.

Yet several social processes appear to countervail, or at least weaken, the pacemaker effect of extremes. Recent analyses of (and debates over) attribution of extreme events to climate change (Dole et al., 2011; Rahmstorf and Coumou, 2011) reveal that even events that could easily be once-in-a-lifetime experiences for those involved do not unambiguously signal trends, nor necessarily convince decision-makers that they are experiencing climate change or are already in a fundamentally different climate (Adam, 2011; editors, 2011). A recent survey reveals that Americans rather readily attribute extreme weather to anthropogenic climate trends (Leiserowitz et al., 2012), but this does not necessarily yield more public support for mitigation or adaptation investments . Both lay and technical people seem more puzzled than provoked by extremes in this awkward era in which anthropogenic climate change is widely predicted, and perhaps just barely discernible (Seneviratne et al., 2012), yet is still hotly debated (Risbey, 2008)

Limits on the effectiveness of hazard mitigation across decades of extreme events (White et al., 2001), some that expressly evoked policies meant to curb future losses (Birkland, 2006), cast further doubt on the notion that extremes might be counted on to propel effective adaptation to a changing climate. And the prescription frequently offered that we should better adapt to *current extremes* as a first step in adapting to *future climate change* (often framed as low- or no-regrets options) implies an inadequacy of current adaptation that, for some unspecified reason,

---

[1] Paper prepared for Adaptation Futures: 2012 International Conference on Climate Adaptation, Tucson, AZ. With support from the Western Water Assessment, and modeling assistance from Mary Huisenga using *Analytica* ©.

remains unfixed, and embodies several implicit, questionable assumptions about efficient land and resource use, and the role of risk in economic development (Hallegatte, 2011). The no-regret prescription also founders on a simple planning logic that would question additional investment in adapting to current conditions that appear destined to change significantly in the near future in unknown ways. This conundrum led Hallegatte (2009) to propose shortened planning horizons as one strategy for adaptation.

This paper reviews these and other propositions on the role of extreme weather and climate events in shaping adaptation to climate change. Case studies of recent experiences in the U.S.A., and simulation modeling of hypothetical adaptation pathways, are used to explicate these effects in resource and hazards management.

A Propositional Inventory

Table 1 offers a propositional inventory of the pace-making role of extreme events in climate adaptation. Arnell et al. (2005) concluded that “Virtually all research into adaptation to future climate change has focused on ‘conventional’ gradual climate change…”, suggesting that we know much less about how societies might respond to extremes climate change, or to marked changes in extreme events as climate changes. The most common assertion is that extremes act as a wake-up call and create a “window of opportunity” for adaptation and risk reduction, a phenomenon well-known to natural and technological hazards researchers: adaptations emerge most strongly and most quickly after extreme events and their impacts (Birkland, 2006). Such “focusing events” not only evoke action where delay had ruled, but set in train adaptation pathways that flavor responses to threats for decades to come (Birkland 1997; 2006; Rubin et al. 2006a; 2006b); a similar pattern of ‘policy acceleration” has been documented for flood response in Britain (Penning-Rowsell et al., 2006).

This policy acceleration is not always an efficient process for mitigating hazards stemming from a stationary climate, and its efficiency in a non-stationary climate remains to be evaluated. Larsen et al. (2008) called on damaging extremes to pace the incorporation of adaptive capacity in reconstruction of Alaskan infrastructure. Extremes may also evoke both consensus to adapt and innovative approaches. Finally, extremes might be seen as signaling future conditions. All of these processes appear to be underway in Vermont’s recovery from Hurricane Irene floods, a case study further described below.

Countervailing processes include the potential for rare events to confuse the sense of climate change, especially if they point in the opposite direction (a deep freeze during a period of generally warming temperatures), this could also act to miscue decision makers. And adaptations made under extreme conditions might turn out to be mal-adaptive.

Table 1 Propositional inventory of pacemaker effects of extreme events.	
Pacemaker Effects	
Wake-Up Call	Extreme events reveal social vulnerabilities and exposures, thus expanding the range and population of areas and people at risk.
Creative Destruction	Adaptations can be added more cheaply when infrastructure is repaired or replaced following a damaging event (as opposed to retro-fitting), Larsen et al.'s *Event Adaptation*.
Creative Innovation	Extreme events evoke innovative responses, new ideas, and reveal previously-unrecognized options (e.g., like water sharing among cities).
Consensus Building	Extreme events bring awareness, sympathy and solidarity to finally "do something" about a local or pervasive vulnerability
Directional Signaling	Extreme events reveal the direction of underlying trends and the potential for increased damage in the future.
Countervailing Effects	
Just MORE Noise!	Rare events actually confuse the sense of climate change, mask trends, and can trip premature adaptation.
Mis-Cueing	Extremes may point in the wrong direction
Traps and Risk-Spirals: Bad choices *in extremis*	Bad choices *in extremis* may exacerbate risks and vulnerabilities (e.g., build higher levees rather than retreat from floodplain)
Over-estimation of the adaptation deficit	How much un-met demand for hazard reduction exists in the stationary case? What are the practicable "no regrets" or "low regrets" options?

Pace-Making Theory and Mechanisms

Adaptation to a changing climate is, like other decision-making processes, variously conceptualized, depending on disciplinary perspective, sector, and the divide between diagnostic and prescriptive analysis (Adger and Barnett, 2009). But it can broadly be captured on a small set of dimensions including: anticipatory vs. reactive; autonomous vs. planned; individual vs. collective; and incremental vs. transformative adaptations (Pelling, 2010; Smit and Wandel, 2006). Sector-specific models of the adaptive process have been offered for farmers (Chhetri et al., 2010), coastal dwellers (Yohe et al., 1996; Yohe and Schlesinger, 1998), and water supply managers (e.g.,), among other decision-makers. More attention recently has been paid to tactical aspects of adaptation, especially pacing. Besides offering rosters of possible adaptations in everything from water resources to international security, the U.S. National Research Council's "America's Climate Choices" report also called for more research on processes of adaptive decision making and the timing of adaptive actions as climate changes unfold (National Research Council, 2010).

Early Formulations

The pre-eminent case of extreme events viewed as pacing adaptation in the U.S. springs from the long literature on response to the flood hazard (White, 1945; Platt, 1996). This frame was extended to drought on the Great Plains when Warrick (1975) established the interpretation in a graphic (Fig. 1) widely emulated in drought studies (e.g., Bowden et al. 1981) to this day. Riebsame (1991) envisioned droughts as tripping step-functional adaptation to a worsening of Great Plains climate (Fig. 2). In the recent climate change adaptation literature this process might be called learning loops (IPCC, 2012) or adaptation action cycles (Park et al., 2012).

Early formulations of extremes-paced adaptation also entrained the potential for mal-adaptation, especially if the adaptive response furthered control efforts like dams and levees (White, 1945), another idea still current in hazards analysis (Harries and Penning-Rowsell, 2011) and strengthened via development of resilience theory (Folke et al., 2010), and applied to expected adaptation to climate change (Penning-Rowsell et al., 2006).

Adaptive Processes

Schneider et al. (2000) earlier posited a conceptual model of adaptation that encompassed the nature of the climate signals, the decision context, and the choices available to the decision-maker, arguing that absent a reliable climate prediction, the adaptive agent must judge based on observation, experience, and policy guides (p. 204). They and others further elaborated this model as a “bottom up” strategy, with attention to: the rate and qualities of climate change; the process of recognizing change and deciding to adapt; the tools available and recognized for adaptation; and the process of evaluating, and choosing adaptive tactics and strategies. Others have since echoed the call for more attention to details of this process (Smit and Skinner, 2002), and specifically called out the role of extremes in the process (Patt et al., 2010).

Schneider et al. (2000) foreshadowed a pacemaker formulation of extremes, postulating that, while climate variability tends to mask trends and thus adaptation, extreme events can override this effect and enhance adaptation efficiency. But they also suggested that that extremes could in some cases “prompt false starts leading to maladaptation.” p. 204. Such formulations of adaptive process center on the individual decision-maker. But extremes might also occasion policy and other programmatic changes that entrain collective adaptation (Arnell et al., 1984). In a sense, individual decision-makers could be forced to adapt even without recognizing change if they are embedded in social instrumentalities (e.g., large flood control systems, building codes, and engineering standards) that exogenously alter the legal, economic or physical conditions of their land and resource uses.

Füssel (2007) laid out a hypothetical planned adaptation storyline in which extreme events and recognition of underlying climate change are drawn on to guide and enable adaption. My colleagues and I use variants of his graphic (Fig. 3) to develop scenarios of adaptation problems, and in this paper they are used to illustrate case studies (below). A recent thread of analysis with a strong focus on pacing attends to infrastructure life-cycle (Kirshen et al., 2008; Larsen et al., 2008; Neumann and Price, 2009). Neumann and Price (2009) argued that centralized programs to up-grade building codes, engineering practices, and other policies affecting the built environment and land use, could accelerate adaptation above what individuals would chose to do, though they also allowed that property owners and investors might resist new requirements that add costs. While programmatic changes have the potential to effect substantial adaptation, institutionalized adaptations to current climate, such as the very flood plain policies set in motion by past extremes, are often viewed as a *barrier* rather than aid to adaptation (Moser and Ekstrom, 2010; National Research Council, 2010). Similarly, professional practice and policy might slow adaptation in water resources planning (Stakhiv, 2011).

Adaptive Stickiness

Though postulated adaptation behavior ranges from severely constrained by cognitive and other limits (Parry et al, 2007) to anticipatory and even clairvoyant (Yohe et al., 1996), most IAV attention is given to limits and barriers to adaptation (Moser and Ekstrom, 2010). It is widely assumed that adaptation will be a reactive, sticky process where many cognitive, technological and political filters will slow responses beyond the point of efficient expected utility, thus yielding a gap between theoretically optimal and actual adaptation (see review by Adger et al., 2007). Adaptive stickiness is likely strongest in the face of the most costly and transformative adaptation choices, such as abandoning shoreline developments (Kates et al., 2012), suggesting that a growing mal-adaptation will hold for some cases.

Yohe et al. (1996) postulated that individual or community decision-makers would fail to respond to rising sea level efficiently by either over- or under-investing (e.g., perhaps investing more to protect property than likely returns would dictate, or abandoning land too early). They predicted more of the latter, suggesting that: "since protection decisions will likely be made at a local level where the political pressures brought might be most powerful, these components could lead to economically inefficient but socially and/or politically prudent efforts to protect coastline that the economic cost calculus would say should be abandoned." (p. 391). The pure version of this posture is termed the "no-foresight" case, in which the decision-maker is surprised by the climate impacts or simply ignores information about the threat until the costs of doing so become quite burdensome, a behavior noted in the natural hazards literature as early as the 1960s (Kates, 1962) and extensively documented since (White et al., 2001). Yohe et al. write that "the no-foresight case covers a more intuitive view of how the future might unfold with coastal property owners maintaining their structures to the bitter end" (p. 392), a description suggesting something more than lack of foresight, akin to denial. The "bitter end" is probably a storm surge.

One factor often not formally considered in expected utility models, but probably yielding delayed adaptation, is expectation of government aid, which in the natural hazards literature is shown to dampen some mitigation behaviors (Burby, 2006; Kunreuther, 2006; Kunreuther and Michel-Kerjan 2007), offering another "Moser-Ekstrom barrier" to adaptation (Moser and Ekstrom, 2010).

Chhetri et al. (2010) elaborate the Schneider et al. (2000) adaptation model with a lag factor that forced sub-optimal adaptation choices into their agricultural adjustment model. Specifically they cite farmers' difficulty of discerning a worsening climate trend from natural variability, a straightforward cognitive brake on adaptation. Indeed, the literature suggests that resource systems marked by large variance will be the slowest to adapt to an underlying change; Coulthard (2009) suggested such a lag mechanism in fisheries in decline: "catches oscillate and this may serve to relight hopes of a return to better incomes--a reason to remain a fisher, and to disagree with the perceived crisis" (p. 263). The difficulty of reducing fleets amid fishery declines, even with strong regulatory and compensatory mechanisms, perhaps presages the challenges of encouraging transformative adaptation to climate change in many other activities and sectors (Kates et al., 2012). But more pertinent to extremes, such an effect could imply that systems naturally marked by extremes, might actually be the slowest to adapt! This behavior is indeed found for a simulated farm, as discussed below.

Overcoming Stickiness: The "Pressure-and-Release" Model

How might extreme events drive adaptation? At least three major possible modes present themselves. First, extremes might serve to propel autonomous, even inadvertent, adaptation, without recognition of worsening impacts. A more common argument is the extreme convinces decision-makers that either (a) social systems are becoming more vulnerable, or (b) natural systems are becoming more extremes, or (c) both, and sets in train purposeful and targeted adaptation. Finally, the extreme damages or destroys infrastructure and other forms of wealth and provides the opportunity for adaptation in the recovery and reconstruction process.

This is generally referred to as the "pressure-and-release" model in natural hazards research. In the climate change case, extreme events provide the release from anti-adaptive pressure especially if they are linked to at least weak belief in underlying climate change. In a mode where climate change is recognized, but has not yet risen to a threshold where proactive adaptation becomes ensconced in design standards and professional and individual practice, adaptation would be accelerated for each damaging or loss-inflicting event, that is if it points in the direction of the expected or perceived underlying change. This is not to say that expected or perceived trends signaled by extremes are, necessarily, accurate foreshadowing of changing climate, so the potential for mis-cueing remains, and must be accounted for in any analysis as false positives.

The "creative destruction" mode is in some ways the most fascinating, and natural hazards experience suggest it might quite plausibly be the main adaptive mode in a rapidly warming world. The "no foresight" ocean-side residents postulated by Yohe et al. are not immune to the physical impacts of storm surges, and one framing of extreme events is that they literally force adaptation by destroying infrastructure and other wealth, thus invoking re-construction during which the adaptation deficit is most efficiently addressed. Still, even this creative destruction hypothesis only holds if decision-makers accept that a given event portends worse or more frequent (or both) events in the future. Another "100 year flood" or "standard project hurricane" is not necessarily cause for altering land use, especially if zoning and insurance programs are already adapted to it (Stakhiv, 2011).

Extremes as Pacemakers

The pacemaker model can be interpreted, and is here analyzed, as both an empirical description of the adaptation process and as a normative prescription for decision-making, especially under conditions of deep uncertainty about trends and the future evolution of climate. The most agnostic adaptation posture, then, partakes of some of Hallegatte (2009) five prescriptions, especially the notion of shortened project horizons, just-in-time adaptation, and safety margins. The prescriptive pacemaker framing then is a hybrid model in which documented climate trends and increasingly credible and specific predictions of future climate set the stage for extreme events to act as triggers of substantive changes in technology and policy that effect adaptation. This evokes an extremes version of a Füssel (2007) adaptation storyline (Fig. 3). Fussel offers a hypothetical situation when a community experiences an extreme (E_1) outside the normal coping range:

> The community wonders whether E_1 is still an expression of natural variability or whether it is already a harbinger of more climate change to come. If the first, the community would be willing to accept the damage because the return period of a similar event would be very long. If the second, the community would prepare for costly extension of their

> coping range because a previously ‘‘unusual’’ event like E_1 would become increasingly ‘‘normal’’ in the future. (p. 267).

In the pacemaker mode, each event that appears to be consistent with the assumed climate trend would act as a trigger to overcome adaptive stickiness. Bigger events would yield more adaptation, but the key difference is that the event is assumed a harbinger of more to come, thus the scales are tipped to adaptive responses, as opposed to the assumption of climate stationarity. Furthermore, the event-driven pattern of adaptation might quicken the infrastructure replacement cycle, and, assuming that infrastructure most in need of adaptation is more likely to be compromised or damaged by extremes, provides a prioritization of adaptive intervention, re-design, and shoring up. This adaptation strategy could be seen as an informed, efficient ”muddling through” (Lindblom, 1959), adaptation that is both reactive and forward looking, actuated more by acute impacts and losses instead of anticipated loss of expected utility, while also enjoying the option value of waiting-and-seeing, acquiring the information and greater certainty of climate trends and risks that comes packaged with extremes.

Two recent studies that apply life-cycle analysis to infrastructure stressed by climate change (Thames; and Larsen et al., 2008) indicate that incorporating adaptations to current and anticipated climate stresses not only at the point of conventional rehabilitation or replacement, but opportunistically when the system is damaged by extreme conditions, hastens adaptation and reduces the long-term costs of climate change. Of course such adaptive posture is more efficient if the direction of change is obvious and marginally advances adaptation investments. Even in the case of response to sea level rise, where the direction of change is well-established, studies find decision challenges at the point where further protection is less efficient than abandonment and in the timing of significant infrastructural augmentations (like sea walls) which, given their costs, may be best delayed until “just in time” to prevent inundation by SLR trend (Neumann and Price, 2009; Titus, 2011; Yohe et al., 1996; Yohe and Schlesinger, 1998), but might be appreciated earlier for their ability to protect from extremes regardless of SLR. Moreover, once large-scale infrastructure is in place, path dependencies make alternative adaptation less likely. Of course, coastal communities lacking physical protection from storm surges and facing accelerating sea level rise may well envy those who, after some previous “accelerating event” (e.g., the 1900 Galveston Hurricane), marshaled the political, economic, and technological will to build a sea wall, and only have to up-grade it rather than go through an elaborate planning and regulatory process, to get on the structural protection path.

One problem with the life-cycle adaptation model is that it tends, of course, to apply to built things, not to land or location, and one of the hardest choices that people make is to change location and/or resource systems, not just because of attachment to place, but because of the non-fungible nature of land. The main mechanism by which most land owners move (either their residence or business) to another parcel is by selling the one they occupied previously---an option that might be extinguished by some climate impacts. It is possible though, that the transaction costs could be obtained by selling the current land for a different use, maybe even an adaptive use (e.g., a shoreline residential parcel is sold to a land conservancy to be restored to active dunes that provide resistance to future storm surges; or the uses of dry land are changed to match the wetland characteristics that parcel has taken on due to SLR). In this way, incremental adaptation, even if tripped by extreme events, blends into transformational adaptation, about which much less has been written (see Kates et al., 2012).

Why Extremes Can Fail to Drive Adaptation

Three countervailing processes interfere with the role extremes can play in pacing/accelerating adaptation. First, extremes in some cases, instead of being viewed and assessed as essential warning of what's to come in the future, might be discounted, in two main ways:

(a) via a broad social and psychological discounting (Pidgeon and Fischhoff, 2011) whereby the notional interpretation of an extreme vent is that it is simply so rare and unlikely to occur again in the foreseeable future that there's no point in preparing for the next occurrence right now, just after this one; and (b) by a set of subtle, but pervasive, technical analytical approaches developed and applied over decades in key fields like water resources development, natural resources management, and infrastructure investment, serve to discount the affect of extremes on planning and adaptation. Stakhiv (2011) recently posited four key biases against weighing extremes and significant future change, what he called the "quadruple discount dilemma" (p. 1192) : wide application of the Log-Pearson statistical distribution to calculate magnitude/frequency relationships for floods and droughts that understates the tails of the distribution; economic discount rates that diminish both the risk of rare events and the value of up-front investments to deal with them; use of expected annual damages (the probability of the event in any given year, which is by definition quite small for extreme events, times the losses it would causes, which are quite large); and an optimization decision criterion requiring that projects be sized to produce the greatest net national benefits, which imposes a macroeconomic efficiency not always consistent with efficient or desirable case-by-case risk reduction or project robustness, much less with anticipated changes in future risks.

Cases: Extremes-Driven Adaptation

No roster of case studies has been developed yet to examine adaptation to extremes from the point of view of climate change, but the IPCC special report on extremes makes a start, and, in a sense, the hazard literature is replete with case studies that have been called on to illuminate potential climate change impacts and responses (for example, Hurricane Katrina in the U.S.). A very initial roster drawing on some 30 years of climate impacts literature (e.g., Kates et al., 1985), and limited to the U.S. and Canada (Table 2), would include events such as the rapid rise of the Great Salt Lake in the early 1980s; the 1988 nationwide drought and heat wave; the Quebec ice storm,; western drought in 2002; and the 2004 hurricane season in Florida.

The first case taken up here might best be seen as an example of a miscue: Utah's Great Salt Lake, a terminal lake in the Great Basin, rose to record levels in the early-1980s due to a spell of wet weather and record snowpack, flooding subdivisions and damaging infrastructure. When in 1983 it began to threaten to inundate both the international airport and I-80, the state invested $60 million in a grand pumping scheme that would, for the first time ever, allow control of the upper ranges of lake levels (Morrisette, 1988a, b). The lake, however, fell naturally just after the pumps began operating (Fig. 4) and they have since been mothballed and might never work again.

Assuming that the extremes do indeed point in the right direction (e.g., notable heat waves riding on an underlying warming trend; or storm surges riding on increasing sea level), then each extreme event-response couplet might well evoke adaptations that reduce future

Table 2 Cases of extremes-driven adaptation that could affect vulnerability to future climate change.

Case	Extreme	Adaptation
1983 Great Salt Lake rise	Wet spell and heavy snowpack; record high GSL level	Pump and canal system to lower the lake; mothballed when lake fell naturally
1988 Heat Wave and Drought	Widespread drought: West (Yellowstone fires); Midwest (Mississippi barges aground); and Southeast: Atlanta water crisis No. 1.	Hansen testimony links drought to global warming
1998 Quebec Ice Storm	Ice accumulation twice the previous record	Glaring vulnerability of critical systems manifest; *Nicolette Commission* adaptations still on-going
2002 Colorado River Basin drought	Record drought in Rockies and Upper Colorado River Basin; new record low Lake Powell volume	Interior Secretary policy on CR shortage sharing added to "Law of the River"
2004 Florida Hurricane Season	Four hurricane landfalls and the most damaging year in state history create an insurance crisis.	State created subsidized insurance system (*Citizens Property Assurance Corp*) for high risk properties.
2008 Iowa floods	Widespread flooding on tributaries to the Mississippi River in Iowa, worse than 1993.	Infrastructure re-location ; flood control strengthening; filed tiling with explicit note that climate change = more rain
2011 Vermont floods (Hurricane Irene)	Historic floods damage 300 bridges, 1,000 culverts and thousands of miles of roadway	Proposed revision of state handbook for sizing hydraulic explicit plan to change infrastructure to accommodate expected bigger events in future.

impacts, that are, indeed, adaptive. This is a special form of reactive adaptation and, because the extremes foreshadow conditions that will become more common in future, it can also be seen as anticipatory adaptation. Drought in the Colorado River basin that peaked in 2002 helped push through a long-discussed reform of the inter-state allocation of shortages left ambiguous in the 1922 river compact and subsequent policies (Fig. 5); the "record of decision" signed by the Secretary of the Interior in late 2007 stated:

> The Colorado River Basin (Basin) is in the eighth year of drought – the worst eight year period in over a century of continuous recordkeeping. Reservoir elevations have declined

> over this period and the duration of this ongoing, historic drought is unknown. This is the first long-term drought in the modern history of the Colorado River, although climate experts and scientists suggest droughts of this severity have occurred in the past and are likely to occur in the future. (U.S. Department of the Interior, 2007, p. 1)

States in the basin were in conflict over shortages caused by the drought and litigation was imminent when the Secretary promulgated the guidelines that had been recognized as a gap in operational plans but had not been needed since the Lake Powell was built in the early 1960s (Fig. 4). The EIS for the guidelines hints at more frequent droughts in the future but fails to mention climate change explicitly in the justification, though a technical appendix assesses the potential for climate change to cause future shortages. A team of climate scientists then analyzed reservoir operations under the new shortage guidelines through 2057 with a 20% decline in flows due to climate change, finding that the new rules reduced the risk of reservoir depletion (Rajagopalan et al., 2009). Assuming the 2002 drought as indicative of extreme conditions becoming increasingly likely due to global warming, then the adaptation appears to reduce the system's vulnerability to climate change as well as episodic drought, though climate change was not invoked in the secretary's order.

Climate change was explicitly invoked as a planning element in the State of Vermont's plans for recovering from flooding associated with Hurricane Irene in 2011. Flooding damaged over 2,000 roadway segments, washed out 1,000 culverts, and damaged 300 bridges, with losses still not fully accounted for at this writing. The state's department of transportation noted that:

> It is recognized that in some cases undersized bridges and culverts played a role in the amount of damage experienced during Tropical Storm Irene. The primary guidebook that engineers use for sizing bridges and culverts on public highways is the Vermont Agency of Transportation's Hydraulics Manual published in 1998. The principles of the manual are founded on risk management associated with various flood levels and statistical analysis of Vermont's historic precipitation data. Since its publication, designers are now considering additional factors not documented in the manual. These include climate change and its influence on precipitation frequency and volume…. (Irene Recovery Coordination Team, 2011, p. 52).

The state's chief transportation engineer noted that:

> Understanding that our climate is changing and that the frequency and intensity of storm activity will likely be greater during the next 100 years than it was during the last 100, it is prudent that as we rebuild we also adapt. But doing so successfully will not be easy………The time has now come, however, to consider building longer bridges with foundations that sit outside our river channels, even if these bridges cost more and have a longer footprint. (Irene Recovery Coordination Team, 2011, p. 56)

But, as with the post-Katrina period, pressure to return systems to normal and to open roads and bridges militate against the sort of re-sizing and reconfiguration that the chief engineer has in mind. This case begs to be followed-up.

Simulating the Pacemaker Effect of Extremes

Two simulation approaches are used here to test ideas about the pace-making effect of extremes in adaptation situations.

The Farmer and the Drought

A simulation model of a dryland wheat farm in the northern Great Plains (Travis and Huisenga, in review) is used here to test the effect of an extreme event (drought) forced into the simulation at various stages of a gradual climate deterioration. The farmer has the option to shift cultivation to a practice (summer fallow) that increases yields in drier conditions at the expense of fallowing land every other year. The model calls for adaptation under specified yield and net income conditions, signaled by the switch to summer fallow in a 30 year run. Drought years forced into the simulations had varying effects on adaptation depending on how extreme they were. Occurrence of the "standard drought" (which suppresses mean yields by about 25%) advanced the beginning of adaptation just 2-3 years whenever it was inserted in the years prior to the point when adaptation would have commenced in the absence of the extreme (compare Fig. 6a to 6b). Once the farmer begins to adapt, that is begins to shift land into summer fallow, the standard drought hastens the process, but again the difference between adaptive and non-adaptive farmers was small for any timing of the extreme event. An "extreme drought" (Fig. 6c), which depresses mean yields by roughly two-thirds, initiates at least some adaptation whenever it occurs in the period before adaptation would have commenced in the absence of the extreme. In Fig. 6b I plot the event in 1998, but the effect was the same in any year before climate adaptation would have commenced under the gradual scenario; the adaptation advance with increasing drought intensity is shown in Fig. 6 d.

Early adoption of summer fallow due to an extreme drought has the counter-intuitive effect of providing slightly higher net income to the non-adaptive farmer in a few subsequent years, until the underlying gradual yield decline re-emerges to depress non-adaptive income. This effect appears to be the result of what Schneider et al. referred to as "false starts leading to maladaptation." It works out that the severe drought evokes only partial adaptation (partial switch to fallow) and the effect of early suppression in production is not off-set by the reduced input costs of fallow until several additional years of gradual yield worsening finally give the advantage to fallow. This small penalty for early adaptation suggests that farmers might be slightly better off sticking with continuous cropping until climate change effects are clearly manifest.

The Culvert and the Rainstorm

The second system simulated here is stormwater drainage, a ubiquitous form of infrastructure (channels, pipes, ditches, floodways, retention ponds, culverts, etc.) sized to accommodate certain rainfall intensities and durations. We apply a simplified version of the "event-driven adaptation model" developed by Larsen et al. (2008) . [To come]

Conclusions

Does the pacemaker model still harbor the catastrophe and levee effects? Might we adapt in the wrong direction, or make things worse as we try to make them better? A couple of things might go wrong. First, of course, one must be sure that the extreme events do accurately signal the underlying, cumulative trend that is exacerbating those events (in frequency and/or magnitude). Second, skeptics might simply argue that the same path dependencies will hold in many cases: once the adaptive pathway is levees, then the response to a rising sea level even as it is signaled in increasingly high storm surges, is, simply, more and higher levees. If that response can maintain an acceptable level of safety/risk, then fine, but eventually the situation comes to look like the prescriptive frame developed in sea level rise impact studies (Yohe et al., 1996), where protection investments make sense until the marginal increment of additional protection is more costly than the property protected or than the cost of strategic abandonment. Given the stickiness of hazard policy paths, we would not expect a correction (e.g., to abandonment) precisely at the point of balanced marginal costs and losses, but somewhere well into increasing net loss.

References

Adam D (2011) Climate change in court. Nature Clim. Change 1:127-130.

Adger N, Barnett J (2009) Four reasons for concern about adaptation to climate change. Environ. Plan. A 41:2800–2805.

Adger WN, Agrawala S, Mirza MMQ, Conde C, O’Brien K, Pulhin J, Pulwarty R, Smit B, Takahashi K (2007) Assessment of adaptation practices, options, constraints and capacity. in Parry ML, Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (ed.) 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.

Arnell NW, Clark MJ, Gurnell AM (1984) Flood insurance and extreme events: the role of crisis in prompting changes in British institutional response to flood hazard. Applied Geography 4:167-181.

Arnell NW, Tompkins E, Adger WN (2005) Eliciting Information from Experts on the Likelihood of Rapid Climate Change. Risk Analysis 25:1419-1431.

Birkland TA (2006) Lesson of Disaster: Policy Change after Catastrophic Events. Georgetown University Press, Washington, DC.

Chhetri NB, Easterling WE, Terando A, Mearns L (2010) Modeling Path Dependance in Agricultural Adaptation to Climate Variability and Change. Annals of the Assoc. Amer. Geographers 100:894-907.

Coulthard S (2009) Adaptation and conflict within fisheries: insights for living with climate change. in Adger WN, Lorenzoni I, O'Brien KL (eds.) Adapting to climate change : thresholds, values, governance. Cambridge University Press, Cambridge, UK, pp. 255-268.

Dole R, Hoerling M, Perlwitz J, Eischeid J, Pegion P, Zhang T, Quan X-W, Xu T, Murray D (2011) Was there a basis for anticipating the 2010 Russian heat wave? Geophys. Res. Lett. 38:L06702.

editors (2011) Heavy weather. Nature 477:131-132.

Folke C, Carpenter SR, Walker B, Scheffer M, Chapin T, Rockström J (2010) Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15:20.

Füssel HM (2007) Adaptation planning for climate change: concepts, assessment approaches, and key lessons. Sustainability Science 2:265-275.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. Global Environmental Change 19:240-247.

Hallegatte S (2011) How Economic Growth and Rational Decisions Can Make Disaster Losses Grow Faster Than Wealth. Policy Research Working Paper 5617. The World Bank, Washington, DC, p. 18.

Harries T, Penning-Rowsell E (2011) Victim pressure, institutional inertia and climate change adaptation: The case of flood risk. Global Environmental Change 21:188-197.

IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Canbridge University Press, Cambridge.

Irene Recovery Coordination Team (2011) Irene recovery report: a stronger future. State of Vermont, Montpelier, VT, p. 72.

Kates RW, H. AJ, Berberian M (eds.) (1985) Climate impact assessment: studies of the interaction of climate and society, Wiley, Chichester [West Sussex]; New York.

Kates RW, Travis WR, Wilbanks TJ (2012) Transformational adaptation when incremental adaptations to climate change are insufficient. Proceedings of the National Academy of Sciences 109:7156-7161.

Kirshen P, Knee K, Ruth M (2008) Climate change and coastal flooding in Metro Boston: impacts and adaptation strategies. Climatic Change 90:453-473.

Larsen PH, Goldsmith S, Smith O, Wilson ML, Strzepek K, Chinowsky P, Saylor B (2008) Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change 18:442-457.

Leiserowitz A, Maibach E, Roser-Renouf C, Hmielowski JD (2012) Extreme Weather, Climate and Preparedness in the American Mind. Yale Project on Climate Change Communication, New Haven, CT.

Lindblom CE (1959) The Science of "Muddling Through". Public Administration Review 19:79-88.

Morrisette PM (1988a) The Rising Level of the Great Salt Lake: Impacts and Adjustments. Bulletin of the American Meteorological Society 69:1034-1040.

Morrisette PM (1988b) The stability bias and adjustment to climatic variability: the case of the rising level of the Great Salt Lake. Applied Geography 8:171-189.

Moser SC, Ekstrom JA (2010) A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences 107:22026-22031.

National Research Council (2010) America's Climate Choices: Adapting to the Impacts of Climate Change. The National Academies Press, Washington, DC.

Neumann JE, Price JC (2009) Adapting to Climate Change: The Public Policy Response Public Infrastructure. Adapting to Climate Change. Resources for the Future, Washignton, DC.

Park SE, Marshall NA, Jakku E, Dowd AM, Howden SM, Mendham E, Fleming A (2012) Informing adaptation responses to climate change through theories of transformation. Global Environmental Change 22:115-126.

Patt A, van Vuuren D, Berkhout F, Aaheim A, Hof A, Isaac M, Mechler R (2010) Adaptation in integrated assessment modeling: where do we stand? Climatic Change 99:383-402.

Pelling M (2010) Adaptation to Climate Change: From Resilience to Transformation. Routledge, London.

Penning-Rowsell E, Johnson C, Tunstall S (2006) ‘Signals’ from pre-crisis discourse: Lessons from UK flooding for global environmental policy change? Global Environmental Change 16:323-339.

Pidgeon N, Fischhoff B (2011) The role of social and decision sciences in communicating uncertain climate risks. Nature Clim. Change 1:35-41.

Platt, R.H. (1999) Disasters and Democracy: The Politics of Extreme Natural Events. Island Press, Washington, D.C.

Rahmstorf S, Coumou D (2011) Increase of extreme events in a warming world. Proceedings of the National Academy of Sciences 108:17905-17909.

Rajagopalan B, Nowak K, Prairie J, Hoerling M, Harding B, Barsugli J, Ray A, Udall B (2009) Water supply risk on the Colorado River: Can management mitigate? Water Resour. Res. 45:W08201.

Riebsame WE (1991) Sustainability of the Great Plains in an Uncertain Climate. Great Plains Research: A Journal of Natural and Social Sciences 1:133-150.

Risbey JS (2008) The new climate discourse: Alarmist or alarming? Global Environmental Change 18:26-37.

Schneider SH, Easterling WE, Mearns LO (2000) Adaptation: Sensitivity to natural variability, agent assuptions, and dynatmic climate changes. Climatic Change 45:203-221.

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X (2012) Changes in climate extremes and their impacts on the natural physical environment. in Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds.) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, pp. 109-230.

Smit B, Skinner MW (2002) Adaptation options in agriculture to climate change: a typology. Mitigation and Adaptation Strategies for Global Change 7:85-114.

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Global Environmental Change 16:282-292.

Stakhiv EZ (2011) Pragmatic Approaches for Water Management Under Climate Change Uncertainty. Journal of the American Water Resources Association 47:1183-1196.

Titus J (2011) Rolling easements. Washington, DC.

Travis WR, Huisenga MT (in review) The Effect of Rate of Change, Noise, and Extreme Events on the Pace of Adaptation to a Changing Climate. Climatic Change.

White, G.F. (1945) Human Adjustment to Floods: A Geographical Approach to the Flood problems of the United States. University of Chicago Press.

White GF, Kates RW, Burton I (2001) Knowing better and losing even more: the use of knowledge in hazards management. Global Environmental Change Part B: Environmental Hazards 3:81-92.

Yohe G, Neumann J, Marshall P, Ameden H (1996) The economic cost of greenhouse-induced sea-level rise for developed property in the United States. Climatic Change 32:387-410.

Yohe GW, Schlesinger ME (1998) Sea-Level Change: The Expected Economic Cost of Protection Or Abandonment in the United States. Climatic Change 38:447-472.

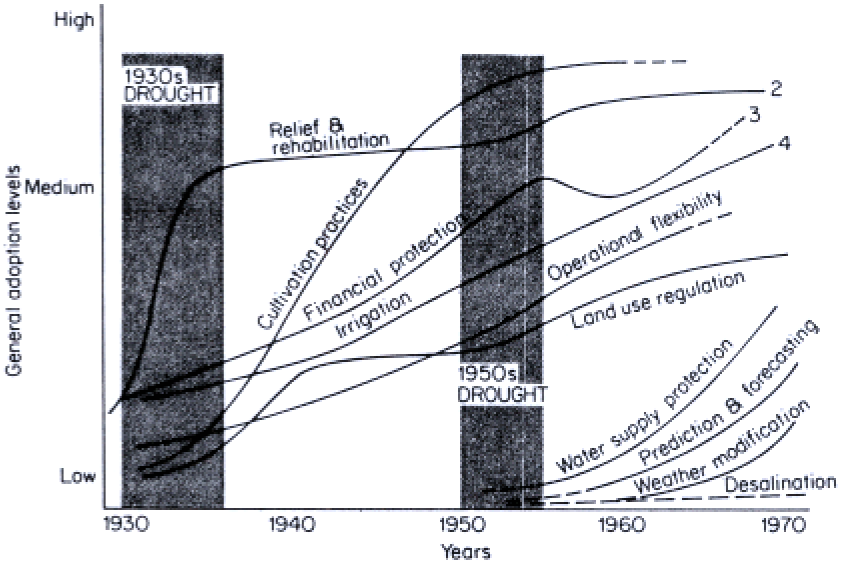


Figure 1: Great Plains droughts cited as pacing adaptation (Warrick, 1975).

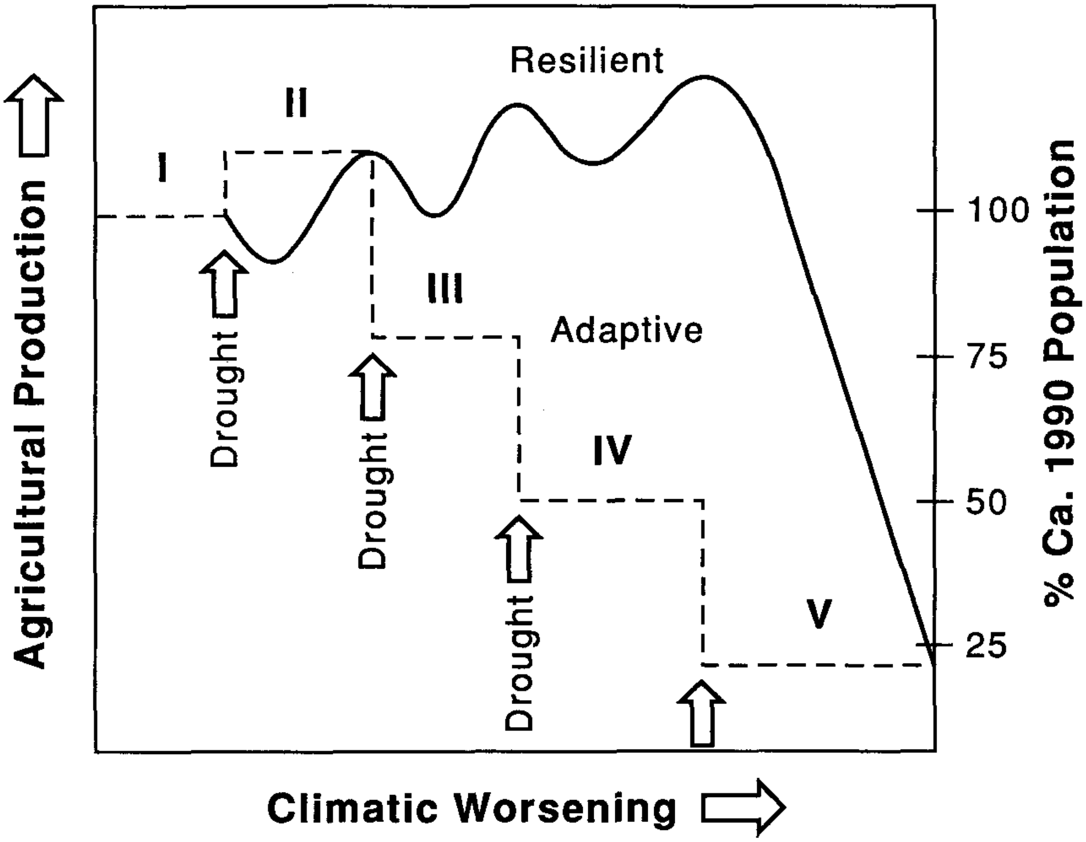
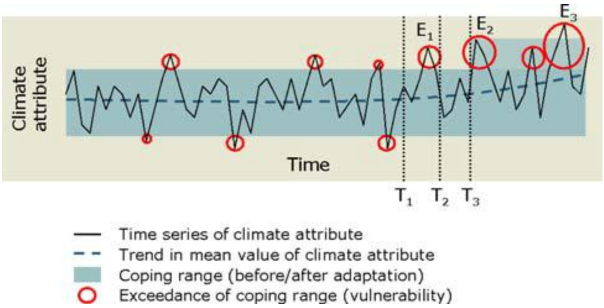
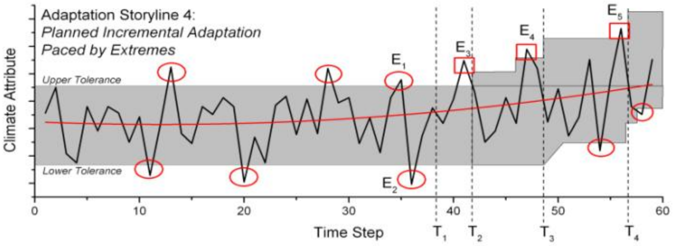


Figure 2: Great Plains drought as hypothetical tripping mechanisms for adjustment to worsening climate (Riebsame, 1990)

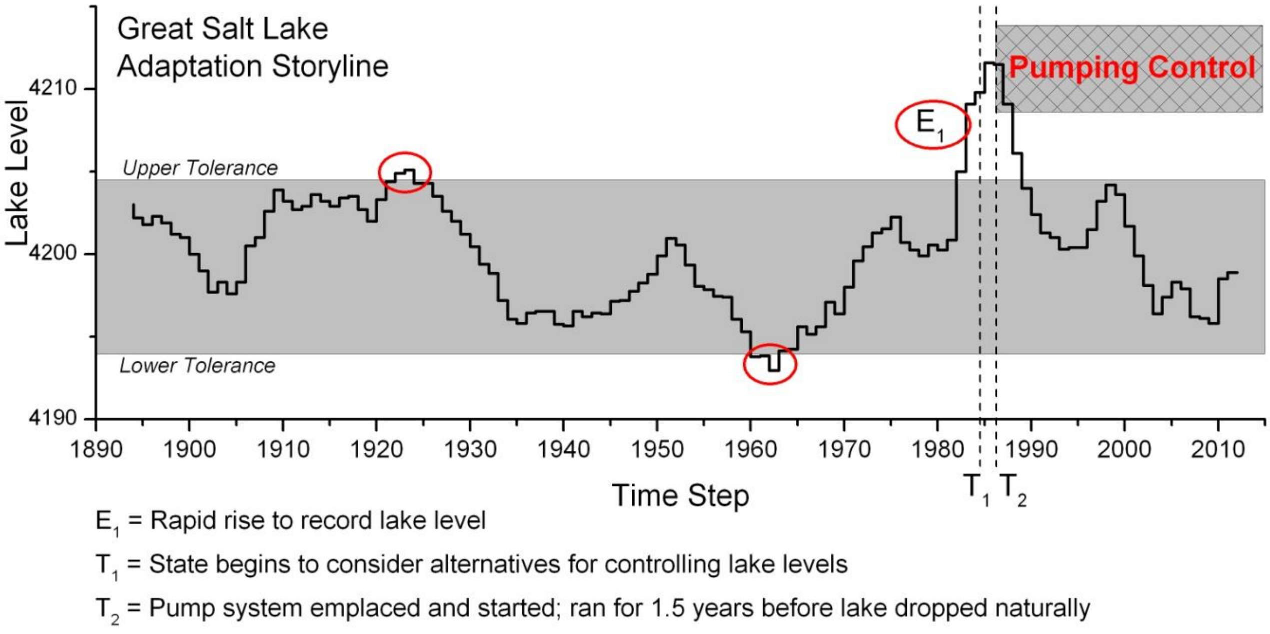
Fussel's (2007)
planned
adaptation
hypothetical





Dilling et al. (see poster here at Adaptation Futures) extensions of Fussel's storyline approach

Figure 3: Fussel (2007) illustration of planned adaptation paced by extreme events, and Dilling et al. extensions to other cases.

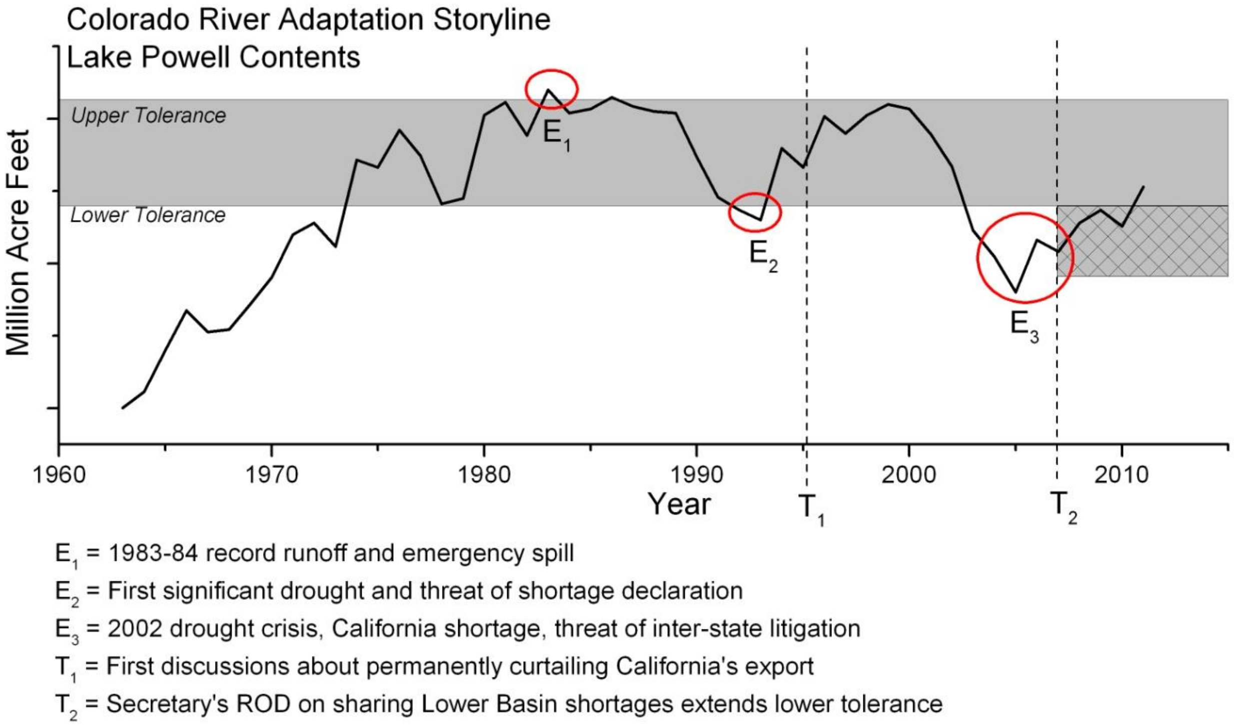


E_1 = Rapid rise to record lake level

T_1 = State begins to consider alternatives for controlling lake levels

T_2 = Pump system emplaced and started; ran for 1.5 years before lake dropped naturally

Figure 4: Case study: Rapid rise of the Great Salt Lake.



E_1 = 1983-84 record runoff and emergency spill

E_2 = First significant drought and threat of shortage declaration

E_3 = 2002 drought crisis, California shortage, threat of inter-state litigation

T_1 = First discussions about permanently curtailing California's export

T_2 = Secretary's ROD on sharing Lower Basin shortages extends lower tolerance

Figure 5: Case study: 2002 drought in the Colorado River Basin.

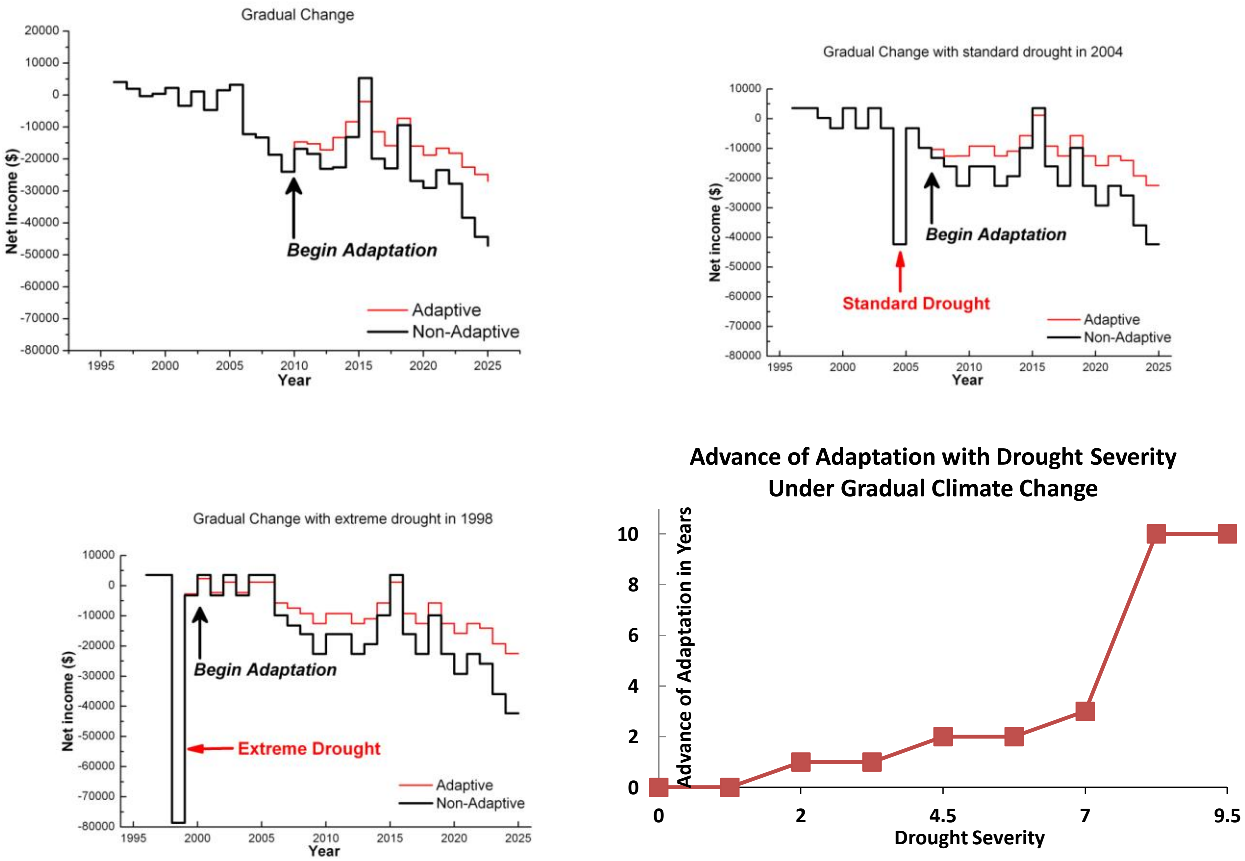


Figure 6: (a) Simulated dryland wheat farm adaptation under gradual climate change; (b) with standard drought I,posed; (c) with extreme drought imposed; and (d) advance of adaptation from gradual change with inserted drought of varying intensity.