



# Spanning “not-improbable” futures to assess relative vulnerability to climate change and climate variability<sup>☆</sup>

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## 1. Introduction

The global-change research community is beginning to turn its attention to assessing the vulnerability of social, economic, political and/or ecological systems to climate change and climate variability in ways that systematically incorporate their ability to adapt. The Workshop on Adaptation to Climate Variability and Change hosted in Costa Rica (March 29–April 1, 1998) by the Intergovernmental Panel on Climate Change (IPCC) stands as evidence of this increased interest. Indeed, the “Scoping Meeting” hosted by the IPCC in late June confirmed that vulnerability and adaptation will be unifying themes in the work of Working Groups II and III as they prepare the Third Assessment Report (TAR). It is reasonable, therefore, to expect a flurry of activity in this area over the next several years.

As the process begins, though, it must be emphasized that the proceedings of the IPCC Costa Rica Adaptation Workshop reiterated the long held belief that long-term uncertainty and near-term variability are ubiquitous. Participants there agreed that

- the processing and dissemination of credible information is a critical component of designing adaptive strategies and sustaining autonomous response processes;
- discerning the signal of climate change from the noise of climate variability will be equally critical in imple-

menting those strategies and sustaining those processes; and

- exploring the extremes of potential impacts for high consequence events will be essential if we are to come to grips with the full measure of our potential individual and collective vulnerabilities.

A natural tension has begun to emerge between conducting careful and detailed analyses of the vulnerability of specific systems to uncertain climate change and significant climate variability, on the one hand, and surveying the globe to identify systems that are most vulnerable, on the other. It is, of course, these most vulnerable systems that are most in need of adaptive capacity, and so it is in analyzing these systems carefully that research will have the largest payoff.

The fundamental research design problem is therefore one of coping with this tension within a binding set of pragmatic constraints. Careful impact analyses designed to incorporate adaptation appropriately into vulnerability assessments are difficult and complicated projects even for relatively closed systems like coastal zones. For relatively more open systems like agriculture, they are even more involved. To see why, simply recall that uncertainty, which cascades throughout our understanding of the climate system, exacerbates the difficulty of assessing impact *cum* adaptation in every case, but especially in those cases where climate variability diminishes decision makers’ abilities to detect secular change. Add to the mix issues of (1) how decision-makers receive information that they deem credible and (2) how researchers can responsibly describe high consequence/low probability outcomes to decision makers, and it is clear that an honest assessment of a large system’s adaptive capacity can take years. As a result, it is unreasonable to expect that complete and timely analysis of each and every system can be accomplished. The selection of those

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systems that *will*, in fact, be the subject of such careful analysis across the full range of plausible futures is coming to the fore as a critical issue.

This paper offers the framework of a simple method designed specifically to help the research community come to grips with this selection issue. It suggests a way that we might build on simple “first generation” impact/adaptation analyses to determine how various sources of cascading uncertainty might alter our understanding of how to plan for what the future might hold. The idea is to apply a vulnerability indexing scheme recently developed by Schimmelpfennig and Yohe (1998) to existing case studies of vulnerable systems (or even heuristic descriptions of sources of stress on systems thought to be vulnerable). Each study or description will have identified critical *impact variables* that drive the relevant climate impacts and frame the associated adaptation questions. It may have worked through some of the possible adaptive strategies for a few climate change scenarios. Perhaps it will have discarded some adaptive strategies that are not “adoptable” given the specifics of their systems’ cultural, socio-economic and political structures. Perhaps it will have looked into the informational constraints that limit the potential efficacy of those strategies. Perhaps it will have placed climate stress and adaptation into the context of the systems’ anticipated responses to other stresses facing the system. Perhaps it will have incorporated climate variability into their considerations. Even if none of these complications has been considered, though, the method to be described here requires only that existing studies or stories identify the critical impact variables that drive prospective change and define the context of possible adaptive response. Indeed, the point of the procedure proposed here is to see if it would be more beneficial to expand our existing knowledge of how a given system might work as the future unfolds or simply to move on to consider another system, altogether.

Once the critical impact variables have been identified for a given system, the proposed method turns to the COSMIC (COuntry Specific Model for Intertemporal Climate) program authored by Schlesinger and Williams (1999) to see if they, or reasonable proxies, are reported. If not, then the game is up for the time being. If they are, however, then long-term trajectories for each impact variable can be traced through COSMIC for as many as 16 different general circulation models (GCMs) along a collection of greenhouse gas emissions scenarios. Some of the emissions paths are drawn from Schlesinger and Yohe 1997, and so model-deduced probabilistic likelihood weights are available. Others emission paths are drawn from the IPCC’s IS92 scenarios. Still others reflect emission paths designed to hold the resulting atmospheric concentrations of greenhouse gases below specified limits. In any case, three different but consistently derived sulfate aerosol scenarios can be attached to any

emission trajectory, and alternative values for sulfate forcing and climate sensitivity can be selected. As a result, carefully categorized representations of the ranges of trajectories for the specified impact variables can be fed into an interpolation process derived from the case study.

It is important to note from the outset that the proposed method is not designed to capture all of the sources of cascading uncertainty that cloud our understanding of climate change. A large part of the reported range of plausible emissions trajectories is captured in COSMIC, and the range of sulfate emissions that can be attached consistently to *each* alternative greenhouse gas emissions path is equally wide. Still, any range of GCM results reflects disagreement across models and not necessarily true uncertainty. Any survey of results may, therefore, understate uncertainty. Notwithstanding this limitation, though, the procedure should help researchers

- to judge when and where careful analysis would be most worthwhile,
- to suggest ranges for the critical impact variables that span much of what might be deemed not to be implausible [a purposeful double negative],
- to highlight ranges for the variables that drive emissions (like population, productivity, and fossil fuel consumption, and so on) that might serve as signals that we are moving into what might currently be considered the low-probability tails of the distributions for critical impact variables,
- to uncover correlations between troublesome scenarios of the future and particular GCMs,
- to suggest where high consequence thresholds might lie and describe how and when we might approach them, and
- to highlight concentration thresholds that, in the words of the Framework Convention on Climate Change, “prevent dangerous anthropogenic interference with the climate system” (Article 2).

Done carefully, this process could, in short, be used to judge the relative likelihood that a threshold of high consequence lies within the “not-implausible” range of impact futures. At the very least, it can help the researcher to look carefully for troublesome concentration thresholds that might be crossed and perhaps to suggest ways of eliminating, or at least reducing significantly, the likelihood of any associated calamitous impacts.

The paper begins in Section 2 with a description of how a careful adaptation analysis might be accomplished. This description is included to make two points. Careful analysis of local or regional impact is, first of all, difficult even in the best of circumstances. Moreover, including adaptation into the analysis can dramatically alter the answer to the ubiquitous “So what?” question.

Section 3 steps back, from the requirements of the sort of comprehensive investigation outlined in Section 1 to report, briefly, the foundations of the simple vulnerability index suggested by Schimmelpfennig and Yohe (1998). Section 4 continues with a review of how the power of the Schlesinger and Williams COSMIC construction might be exploited by the vulnerability index construction. Particular attention is paid there to how COSMIC results might be interpreted and employed to assess vulnerability of a wide set of possible futures. Section 5 reports the results of applying the vulnerability index *and* the COSMIC program to explore the vulnerability of traditional maize agriculture in Mexico to climate change and climate variability over a typically large range of “not-implausible” futures. It offers the potential for good or bad news, depending upon how the future unfolds; and it closes with some insight into which GCMs support which type of news along what types of emissions scenarios. Section 6 reports comparable results under an alternative agricultural regime that has been proposed by the Mexican government. It shows that this officially sanctioned adaptation to climate variability can help, but not as much as might be expected across the full range of possible climate change futures. Concluding remarks drawn from both the methodological construction and its application to Mexico occupy Section 7.

## 2. A schematic of assessing vulnerability *cum* adaptation

Fig. 1 displays a schematic portrait derived from the IPCC Common Methodology for assessing the impact of climate change on a natural, social, and/or economic system (IPCC CZMS, 1992; IPCC, 1994). It has been modified somewhat by the Working Group on Coastal Zones and Small Islands of the IPCC Costa Rica Adaptation Workshop to emphasize the complication of coping with uncertainty and climate variability. Notice, in particular, that it differentiates between *vulnerability assessment*, the point of the Common Methodology, and *adaptation assessment*. The results of the interactions of climate change with other factors as they work through natural and socio-economic systems are depicted as critical components of *vulnerability assessment* – the determination of critical impact variables that threaten the specific system in question. The results of casting those variables, their ranges of uncertainty, and the variability that clouds our vision of their likely secular trends through mechanisms that sustain “autonomous” adaptation and support proactive and/or reactive planned adaptation are depicted as *adaptation assessment*. For either type of adaptation, though, the actors in the system must have processed what they take to be credible information, undertaken some planning or identified some available response opportunities, implemented

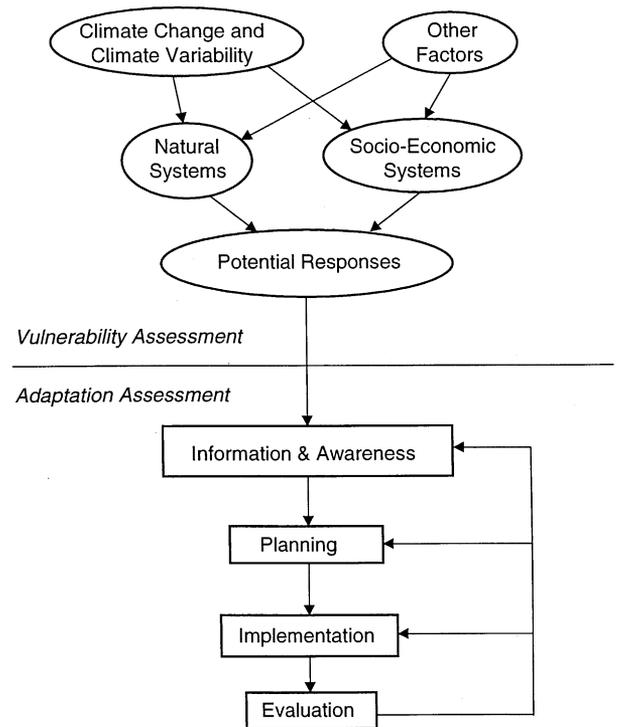


Fig. 1. A schematic diagram of a process by for evaluating the vulnerability of a system to changes in climate and/or climate variability.

those plans or exploited those opportunities, and evaluated their effectiveness in the context of other system-specific structures and distortions. There are feedbacks to each step, and each is more complicated than it might first appear.

Before turning to the complication, though, notice that the process depicted in Fig. 1 is, indeed, a direct descendent of the IPCC common methodology (i.e., the “technical guidelines described in IPCC, 1994). Its very creation builds on the definition of a problem related to changes in climate and/or climate variability (Step 1 of the *Technical Guidelines*). The schematic is flexible in terms of method, primarily because the proper choice varies from place to place and context to context (Step 2). In any case, though, it will become clear that the schematic supports a process designed specifically to explore sensitivity and to use the results to actually select “interesting” scenarios for more thorough analysis (Steps 3 and 4). Finally, the point here is to see how it might be possible to determine when careful assessment of autonomous and strategic adaptation to a range of “not-implausible” biophysical and/or socio-economic impacts might pay the most dividends (Steps 5–7).

Careful consideration of the situations to which the process might best be applied will, however, be complicated. To see this more clearly, one need only recognize

that the “Awareness and Information” box represents processes by which actors in the system

- are made aware of the relevant impact variables that are driving increased vulnerability,
- monitor those variables and/or collect information about their likely and unlikely futures,
- separate the signal of secular trends in those variables from the “noise” of climate variability,
- work through mechanisms and methods of distribution through which decision-makers receive what they deem to be credible information, and
- depict the necessary uncertainties to those decision-makers without undermining credibility.

The “Planning” box is equally complex. It represents processes by which decision-makers

- consider options that are “adoptable” within their system or identify mechanisms by which they might respond autonomously,
- evaluate the relative effectiveness of those options and/or mechanistic reactions to coping with the anticipated secular trends and
- examine the relative robustness of both across the range of uncertainty in the secular trends as effected by the natural variability hides them.

Moving to the “Implementation” box brings the analysis into a more pragmatic sphere, asking researchers to ponder how the system work to make its adaptive plans work or to effect appropriate autonomous reactions. It should be clear that one of the most effective methods of planned adaptation may be simply to facilitate the system’s ability to respond autonomously to change as it occurs and/or to discourage the system’s propensity to mal-adapt in the confusion created by uncertainty and variability. Finally, the “Evaluation” box calls for an on-going process of monitoring not only the critical impact variables for better information, but also the degree to which planned and autonomous adaptation strategies actually diminish the system’s vulnerability to changes and variation in those variables.

Contemplating how a researcher might assess the vulnerability and adaptive potential of a developed community to greenhouse-induced sea level rise can illustrate these points even more explicitly. Vulnerability could, following Yohe (1989), be measured in terms of the economic value of property that would be inundated along any specific sea level rise trajectory through, say, the year 2100. The results could be expressed either as a time series of threatened value, or as a single present value estimate for a specific discount rate. In either case, the results would be trajectory specific, so the process may be conducted along several paths offered by the IPCC in its Second Assessment Report.

Adding adaptive potential to the example would allow vulnerability estimates to be replaced by more germane estimates of the opportunity cost of inundation as in Yohe et al. (1996). Assessing adaptation to the secular trend of rising seas would, in the first instance, require some portrait of how the community might develop over time – a careful elaboration of context. Rising populations, economic growth, further development in vulnerable areas, more elaborate development of existing areas would all need to be considered in the creation of this portrait. The assessment would then have to imagine how the community might come to recognize the threat of rising seas (the “Awareness and Information” box in Fig. 1). It would probably not be enough simply to assert that IPCC results would appear in the communal consciousness without some help – technical help from federal and state agencies, media presentations of sea level rise, and the like. Real estate markets might begin to accommodate the information so that threatened property might decline in value. Insurance companies might be more proactive in incorporating the threat in the premia that they charge for their policies. Local planners might finally begin to contemplate adaptive responses [the “Planning” box]: protecting property (by building sea walls or nourishing beaches), accommodating (by raising structures so that they are less threatened) or retreating from the sea (by effectively abandoning property with decisions not to allow them to be protected). The relative merits of each would be evaluated by some decision criteria (like cost/benefit analysis) on whatever scale was deemed appropriate (from long stretches of shoreline for beach nourishment projects to smaller parcels of land for sea walls). Markets and insurance companies would take note of each of these strategies. They, and the individuals who are involved, would judge both the credibility of the scientific projections of rising seas *and* the integrity of the policy plans. Their judgments could have significant impacts on the decision calculus (e.g., the benefit of a protection project would be higher if a decision to abandon property were not believed so that structure values would not depreciate). All of this would be incorporated in the planning process; and implementation of whatever strategies were selected would proceed [the “Implementation” box]. Evaluation [the “Evaluation” box] would involve monitoring the secular trend to judge when each option should begin – immediately for beach nourishment but as needed for sea walls.

Uncertainty about future sea level rise does not add much complexity; Yohe et al. (1996) has argued that the process moves so slowly that there adequate monitoring should provide more than enough time for effective reactive adaptation. Bringing climate variability reflected by the frequency and intensity of coastal storms to bear on the assessment is, however, a different story.

Dowlatabadi and West (1998) have demonstrated that adding storms to the calculus can increase estimates of the damage that can be attributed to sea level rise even without any scientific judgment that their frequency and intensity might increase with global change. Expanded community development and the amplification of storm surges by higher sea levels can increase the potential for higher damages, but so, too, can the potential of losing the same structure more than once (perhaps once or twice to storms and then again to sea level rise). The information processing problem is, in such a circumstance, complicated by issues of attribution – are higher damages and insurance company liabilities the result of climate change, or the aggravating confluence of inappropriate development, moral hazard, and adverse selection? Planners are, in addition, faced with new sets of decisions: Should exaggerated set-back rules be enacted? Should development in areas that would be particularly susceptible to coastal storm damage be prohibited? Should investments in infrastructure be altered to accommodate aggravated effects of storms and rising seas? Answers to these questions and system-wide judgments of their credibility would again effect the parameters of the protect/abandon/accommodate adaptation decisions; and evaluation would include monitoring the degree to which the application of set-back rules and decisions to abandon are upheld in the legal system.

How much does all of this complication matter? Estimates by Yohe (1989) of the present value of vulnerability for the developed coastline United States for a sea level rise trajectory that reaches 40 cm by the year 2100 run from \$44 billion to \$92 billion (1990\$ with a 3% discount rate). Estimates of the present value of comparable opportunity costs (from Schlesinger and Yohe, 1998) run from \$73 million to \$3.6 billion (1990\$ within a 10th through 90th percentile range) under the assumption that market-based adaptation works perfectly (perhaps in conjunction with insurance premia pressures) to depreciate the values of structures to be abandoned to zero just as they are inundated. They meanwhile run from \$143 million to \$4.4 billion (1990\$) if those same market-based adaptations incorporate no information and/or deem decisions to abandon as entirely incredible. These “second generation” estimates can be as much as an order of magnitude smaller than initial vulnerability estimates because they include micro based decisions to protect or to abandon and because adaptation caps the potential cost of rising seas at the cost of protection. West (1998) has recently shown that including storms can increase the expected cost attributed to sea level rise by as much as 20%. This is not much of a change, but the real message from West is that some “not implausible” sequences of storm events over time can more than double the path-dependent cost of sea level rise on developed coastlines.

### 3. A pragmatic index of vulnerability to climate change and climate variability

Even a brief review of the IPCC Common Methodology makes two points very clearly. First of all, careful analysis of vulnerability *cum* adaptation to climate change and climate variability is difficult, time consuming, and expensive. Secondly, moving from assessing vulnerability to contemplating adaptation can make an enormous difference in judging the relative magnitude of the potential cost of climate change. The previously asserted need for carefully judging how to direct scarce research talent and treasure into areas, systems and/or sectors where the difference between vulnerability and adaptation assessments will be largest should now be equally clear. The pragmatic index of vulnerability devised by Schimmelpfennig and Yohe (1998) represents a first step in making that judgement. It offers a means by which researchers can attach comparable, time-dependent, and unitless measures of vulnerability to an assortment of areas, systems, or sectors; and so it offers a means by which the administrators of climate research can identify when and where vulnerability might be most acute.

The Schimmelpfennig and Yohe construction is really quite simple. Fig. 2 can be used to illustrate its foundation in the context of some arbitrary economic, political, ecological, or other system whose current sustainability is determined in part by two distinct climate-related variables (Climate Variables 1 and 2 to be denoted in the text by C1 and C2). Note that several regions are highlighted in the top portion of Panel A. One region, denoted CV(0), represents the boundary of climate variability in two dimensions at some initial time ( $t = 0$ ); that is, region CV(0) captures the range of combinations of C1 and C2 that can be expected to occur under the current climate. A second region, denoted Sus(0), highlights the boundary of climate variability in the same two dimensions within which the current manifestation of some system (System A) can be “sustained”; analogously, then, region Sus(0) portrays some perception of the combinations of C1 and C2 that will not put undo or intolerable stress on System A. CV(0) does not lie everywhere within Sus(0), so there are some realizations of the current climate for which System A is uncomfortably and perhaps catastrophically stressed. Meanwhile, Sus(0) does not lie everywhere within CV(0), so there are some currently infeasible realizations of climate that would be tolerable.

Schimmelpfennig and Yohe exploit this representation by defining an index of this system’s current sustainability as the likelihood that climate will, in any year under the current climate and associated pattern of variability, bring C1 and C2 within Sus(0). Formally, they define an index for, say, time  $t = 0$  [denoted  $S(0)$  in what follows]

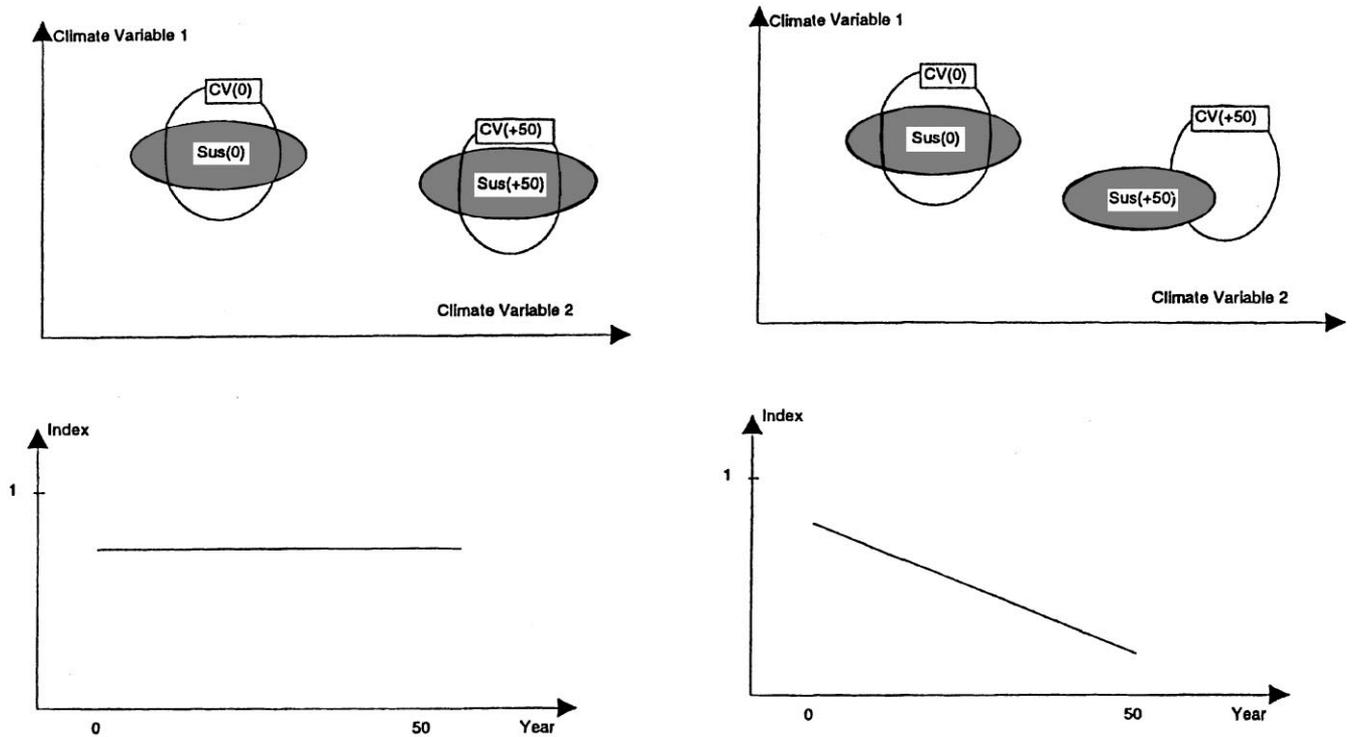


Fig. 2. Depiction of the sustainability index proposed by Schimmelpennig and Yohe (1998). Panel A shows how a system might evolve over time in synch with climate change so that its index number (the probabilistically weighted intersection of the Sus(t) and CV(t) regions) is sustained; Panel B depicts a case where climate change moves away from the system’s sustainable region so that the index falls.

to be

$$S(0) \equiv \int_{CV(0) \cap Sus(0)} f(C1, C2; 0) dC1 dC2, \tag{1}$$

where  $f(C1, C2; t)$  represents the subjective density function under the climate at any time  $t$  [such as  $t = 0$  as in Eq. (1)] for  $C1$  and  $C2$ . Note, of course, that  $1 \geq S(0) \geq 0$  since

$$\int_{CV(0)} f(C1, C2; 0) dC1 dC2$$

is bounded by unity. There is, as well, an associated vulnerability index  $V(0) \equiv [1 - S(0)]$ ; it is the subjective likelihood that the current climate will, in any one year, bring  $C1$  and  $C2$  outside the  $Sus(0)$  region.

Two other regions, denoted  $CV(+50)$  and  $Sus(+50)$ , are also highlighted in Panel A. They are drawn to depict one potential manifestation of System A’s relationship with its climate some 50 years into the future. Since the regions and their intersection are the same as before, Panel A shows that System A has adapted effectively by moving its range of sustainability “east” and “a bit south” as the climate has changed. The lower portion of Panel A depicts this perfect adaptation by indicating that

$$1 > S(t) = S(0) > 0 \text{ for all } 50 \geq t \geq 0 \text{ with}$$

$$S(t) \equiv \int_{CV(t) \cap Sus(t)} f(C1, C2; t) dC1 dC2. \tag{2}$$

An indefinite number of alternative futures for System A can certainly be envisioned, and each can be reflected by associated times series of sustainability indices. Other systems’ vulnerability to the same future can also be portrayed. Panel B, for example, depicts the outcome of some other system (System B) that cannot adapt as effectively over time as System A. This is clear because the intersection of  $CV(+50)$  and  $Sus(+50)$  in the top portion in the top portion of the panel; and so the lower portion traces an index value that declines over time.

The construction is simple enough, but it is remarkably robust. Without reference to currency or structure, it can, for example support the conjecture that System B depicted in Panel B is more vulnerable over time than System A. It is not a stretch, as a result, to expect that a careful consideration of adaptation alternatives for System B would be more beneficial, all other things being equal than an equally careful examination of System A. The construction has, as well, been applied with some success to data drawn from the real world.

Schimmelpfennig and Yohe (1998) applied the method to assess the vulnerability of agriculture in the United States to climate change with and without mitigation policy. Yohe (1997) used its structure to offer a typology of potential adaptive responses to deteriorating sustainability and applied its content explore the sensitivity of wheat yields to simultaneous secular change in precipitation and temperature for two specific locations in the state of Kansas. Both of these applications exploited a wealth of data that described “baseline” scenarios of the future, though; and that is their shortcoming. Data are not always plentiful, and the baseline is not guaranteed.

#### 4. Using COSMIC to represent the “not implausible” ranges for critical impact variables

Suppose, for expositional ease, that some variable  $X$  has been determined to be the critical impact variable for some social, ecological or economic system; and suppose, as well, that trajectories for  $X$  can be deduced from the 16 GCMs reported in COSMIC. Fig. 3 offers a representative sample of output from COSMIC for Mexico drawn from the CCC (Canadian Centre for Climate Research) GCM. Monthly mean temperature and precipitation figures are displayed there graphically for the years 1990 and 2100 along a high-emissions trajectory (S7) with moderate associated sulfate emissions, a climate sensitivity of  $2.5^{\circ}\text{C}$  and sulfate forcing set at  $-1.0 \text{ W m}^2$ . So  $X$ , in this heuristic example, could be precipitation in August. In any case, plotting the estimates offered for each emissions scenario (greenhouse gas emissions and associated sulfate aerosol trajectory) by each of the GCMs produces, for every decade through the year 2100, can be used to produce distributions of future impacts that can be summarized graphically. Any type of distribution could emerge, of course, but a brief description of several can illustrate a “common sense” approach to how they might be used to support a systematic examination of system vulnerability by selecting relevant scenarios that cover adequately a reasonable range of “not implausible” futures. Each case described below.

*Case 1:* A tight and peaked distribution around zero indicates little chance that the impact variable  $X$  will move sufficiently in the future to warrant much attention (unless the system is highly sensitive to small changes in  $X$ ).

*Case 2:* A tight and peaked distribution around a non-zero value indicates a large chance that the impact variable  $X$  will move along a narrow corridor as the future unfolds. Assessing vulnerability at the mean of the distribution should be sufficient to examine the extent of the damage or benefit.

*Case 3:* A tight but nearly uniform distribution around zero indicates the roughly equal chance that the impact

variable  $X$  will move modestly in either direction. Assessing vulnerability at both extremes seems warranted. Comparing the net effect of these extremes would produce insight into whether or not the damage caused by moving in one direction is as large as the benefit generated by moving in the other. In rare cases, damage might be felt in both directions, but the magnitude and adaptive responses might be different.

*Case 4:* A tight but nearly uniform distribution around a non-zero value indicates the roughly equal chance that the impact variable  $X$  will move in significantly in one specific direction or the other. Assessing vulnerability at both extremes again seems warranted. Comparing the net effect of these extremes could produce insight into whether or not the damage or benefit caused by the change increases at an increasing or decreasing rate. Investigating the more distant extreme direction seems a reasonable hedge against missing the source of a high consequence, modestly likely event.

*Case 5:* A wide but peaked distribution around zero approximates Case 3 above and suggests examining the values located well into both tails.

*Case 6:* A wide but peaked distribution around non-zero value approximates Case 4 above and suggests examining values located well into both tails as well as the mean.

*Case 7:* A wide and relatively uniform distribution around zero exaggerates the conditions of Case 3 above; the reasons for the examining extreme values apply even more emphatically.

*Case 8:* A wide and relatively uniform distribution around a non-zero value indicates a large chance that the impact variable  $X$  will move significantly as the future unfolds. This is the most troublesome case, and assessing vulnerability in futures that pick up both extremes as well as an intermediate value that approximates the mean is warranted. The sensitivity of the gradient of damage or benefit across the full range should receive particular attention; and the potential for thresholds of very high consequence events could be high.

Representing alternative distributions when there are two or more critical impact variables would be more a more difficult task, but the common sense pursuit of selecting scenarios to maximize information and explore “not implausible” ranges is the same. Significant correlations between variables could allow a casual application of the uni-dimensional cases just described, but more diverse distributions would be troublesome. Fig. 4, for example, displays a wide, uncorrelated, but somewhat peaked distribution for two impact variables designated  $X$  and  $Y$  that does not contain zero with any significant likelihood. The intuition offered here suggests, however, that choosing representative ordered pairs defined by the unconditional means of  $X$  and  $Y$  [ $\cong(3, 2)$ ] plus three

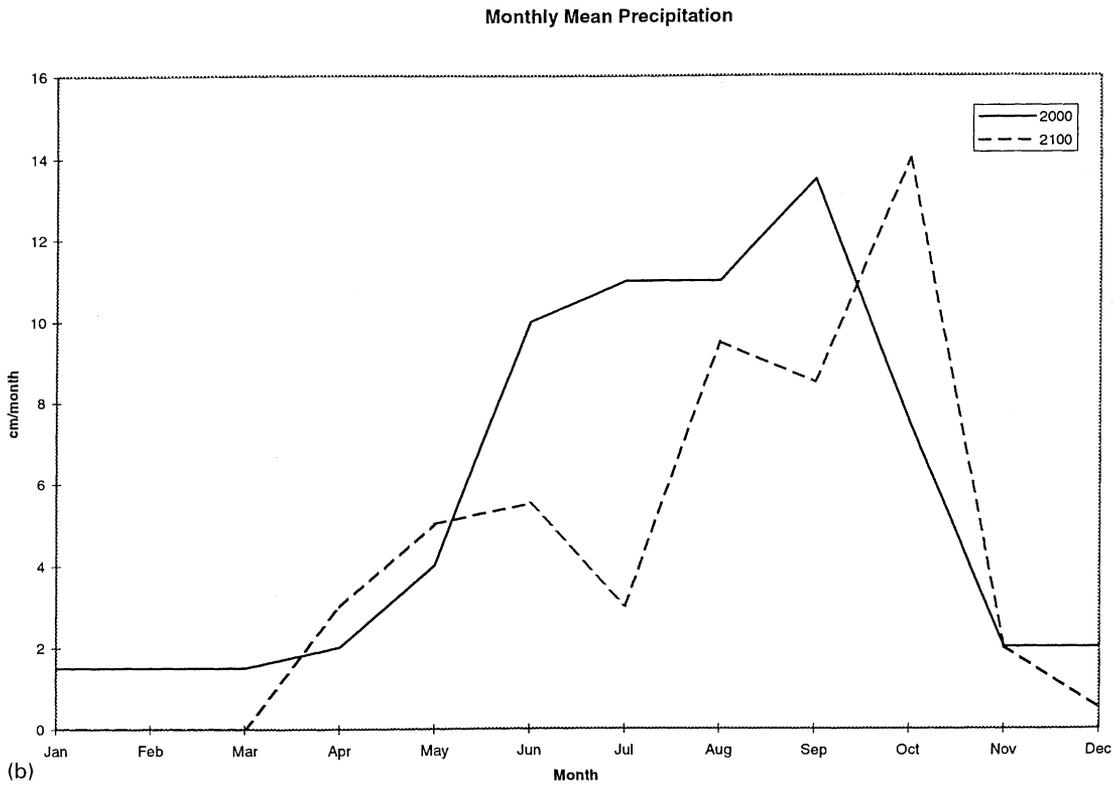
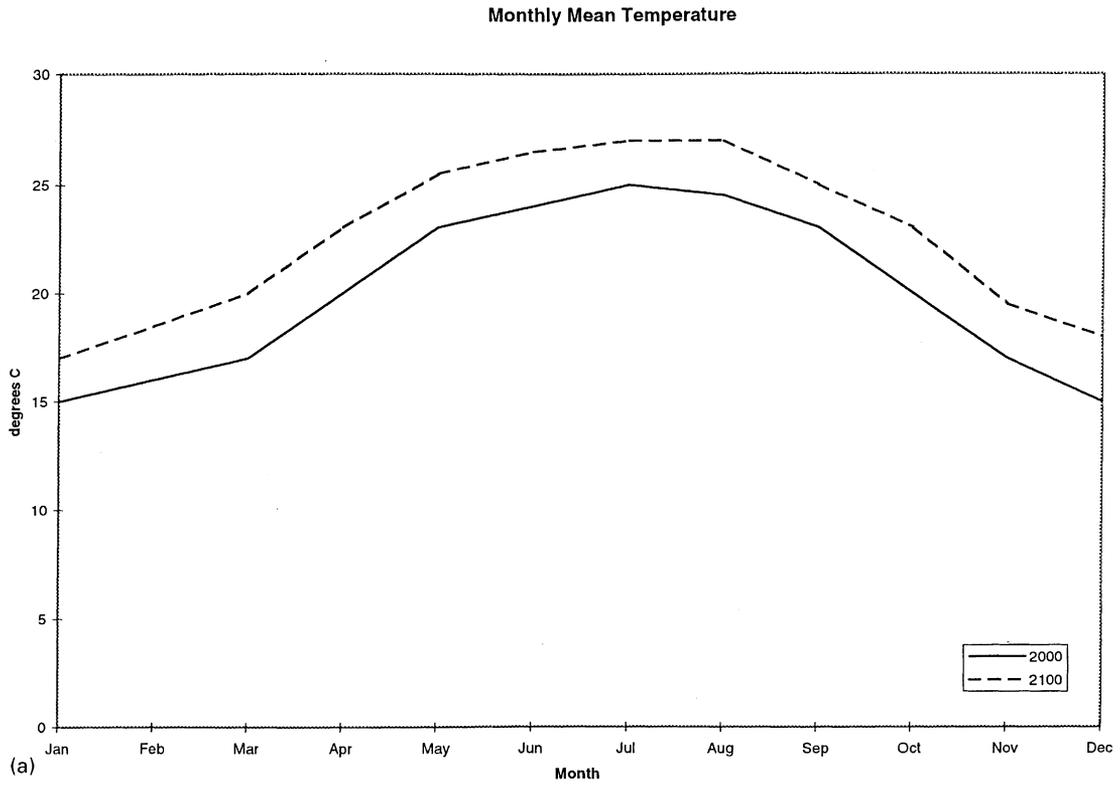


Fig. 3. Sample output from the COSMIC model. Results derived for Mexico from the Canadian Center for Climate Research model are depicted for emissions scenarios S7 (high emissions) with a 2.5° climate sensitivity and moderate sulfate forcing along the middle sulfate scenario.

## Dual Variable Case

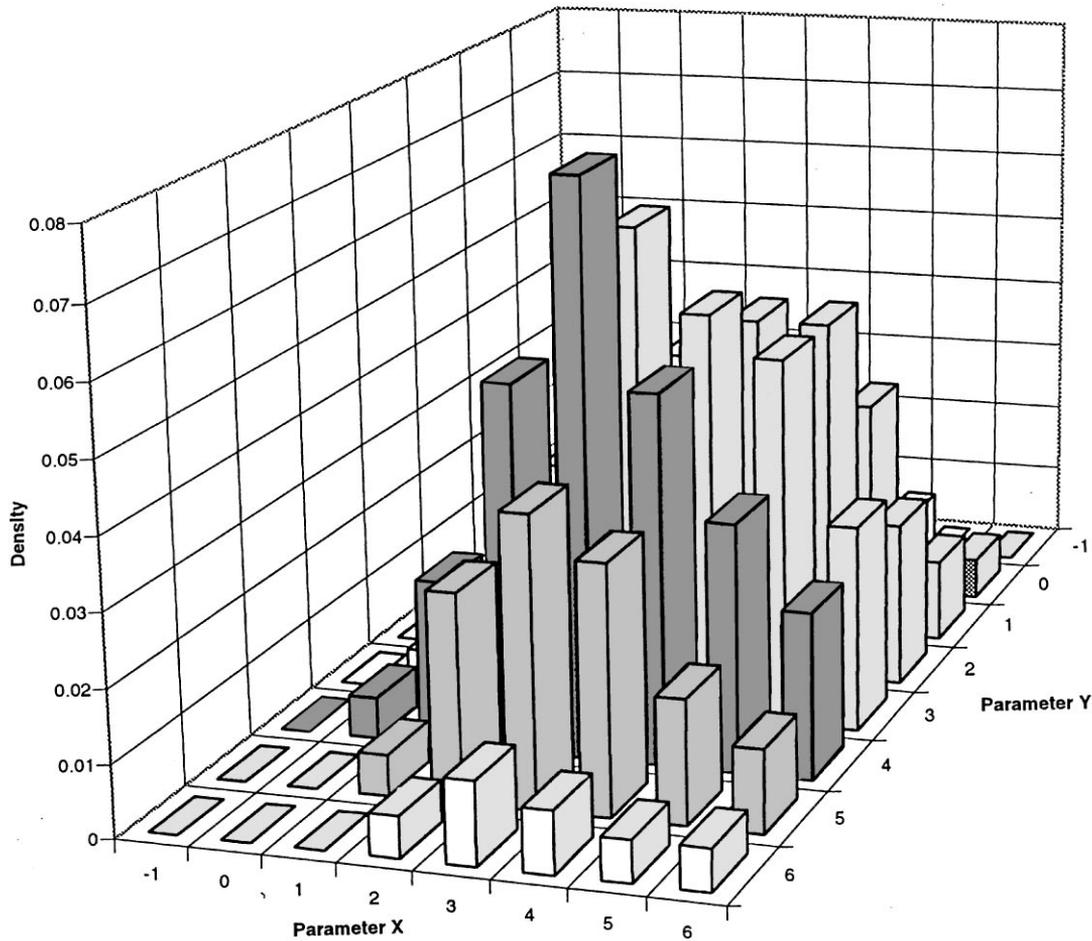


Fig. 4. A sample distribution for two climate parameters.

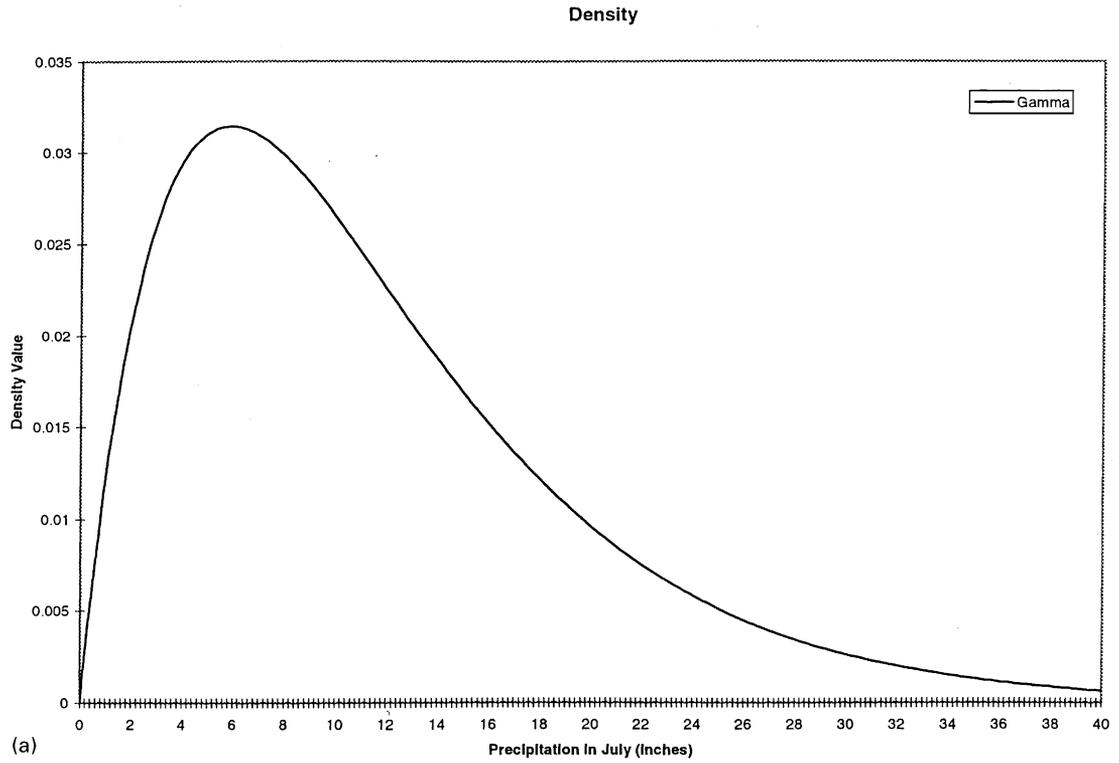
points which surround the mean from above *and* lie near the distribution's extreme values [e.g., (6, 2); (6, 5); and (3, 5)] should be sufficiently representative.

### 5. An application to traditional agriculture in Mexico

Hallie Eakin (1999) reports the results of a case study on the climatic risks faced by traditional agriculture in Mexico. The focus is small-scale maize production in Tlaxcala, Mexico; and considerable attention is paid to the political and economic circumstances that frame this environment. Of particular note for present purposes is the sensitivity of traditional yields to (1) draught in July and August, (2) late frost in the spring, and (3) early frost in the autumn. Eakin notes that commercial maize requires 150 to 200 days free of frost to mature, and so the distribution of rising temperatures into the spring and autumn months can be critical. Precipitation's falling below 50% of the average in July and/or August can be

even more detrimental. Indeed, Fig. 2 in Eakin (1999) suggests that the annual manifestation of the current climate brings this threshold into play about about 30% of the time with associated yields falling below the critical threshold of 2000 kg per hectare.

Panel A of Fig. 5 portrays a typical gamma density representation of July precipitation under the current climate. It has been calibrated so that the mean matches the current 11.7 cm and the likelihood that precipitation will fall below 6 cm (roughly 50% of the mean) is approximately 30%. Panel B posits 6 cm as the corresponding critical threshold expressed in terms of precipitation in July. It portrays what happens to the likelihood of any year's July rainfall falling below this limit as the mean changes; it is, of course, drawn assuming that the general gamma structure of Panel A continues to hold. Notice that 11.7 cm is associated in Panel B with the currently observed 30%. The likelihood of falling below the threshold climbs dramatically as mean precipitation falls; and it falls modestly as mean precipitation rises.



**Threshold Likelihood Versus Mean July Precipitation**

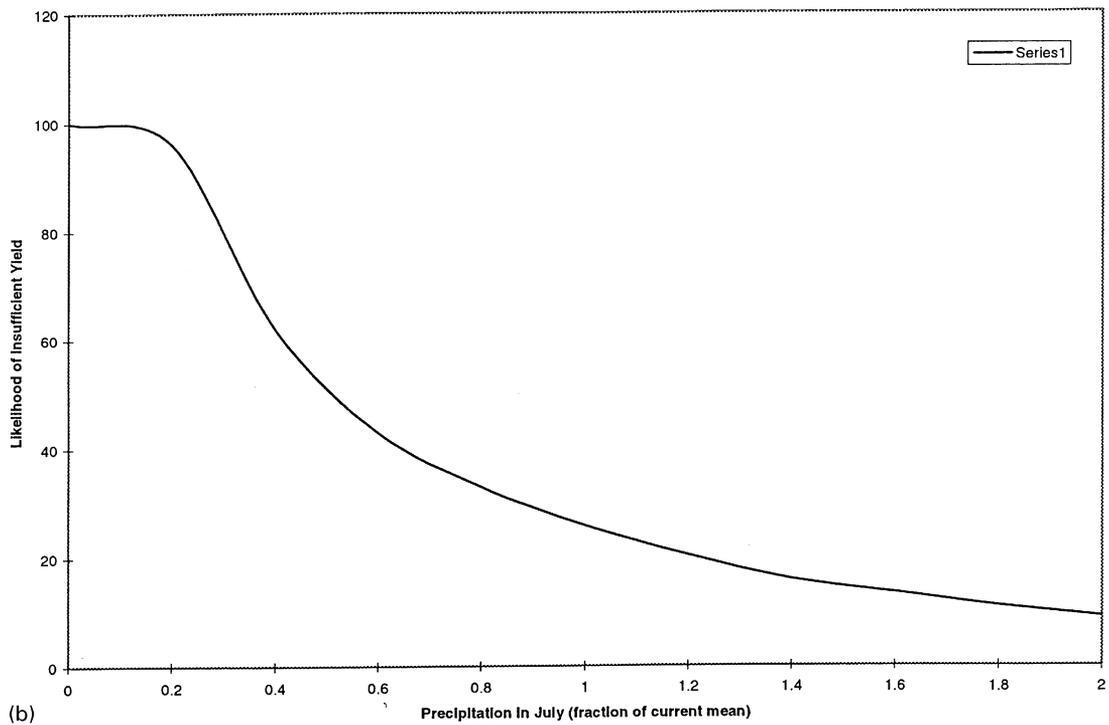


Fig. 5. Panel A depicts a typical gamma distribution for July precipitation in Mexico under the current climate. Panel B portrays the relationship between changes in the monthly mean (as a multiple of the current mean of 11.7 cm) and the relatively likelihood that precipitation in any year would fall below a critical threshold of 6 cm.

## Mexico -- July Precip and Change in Growing Season Length

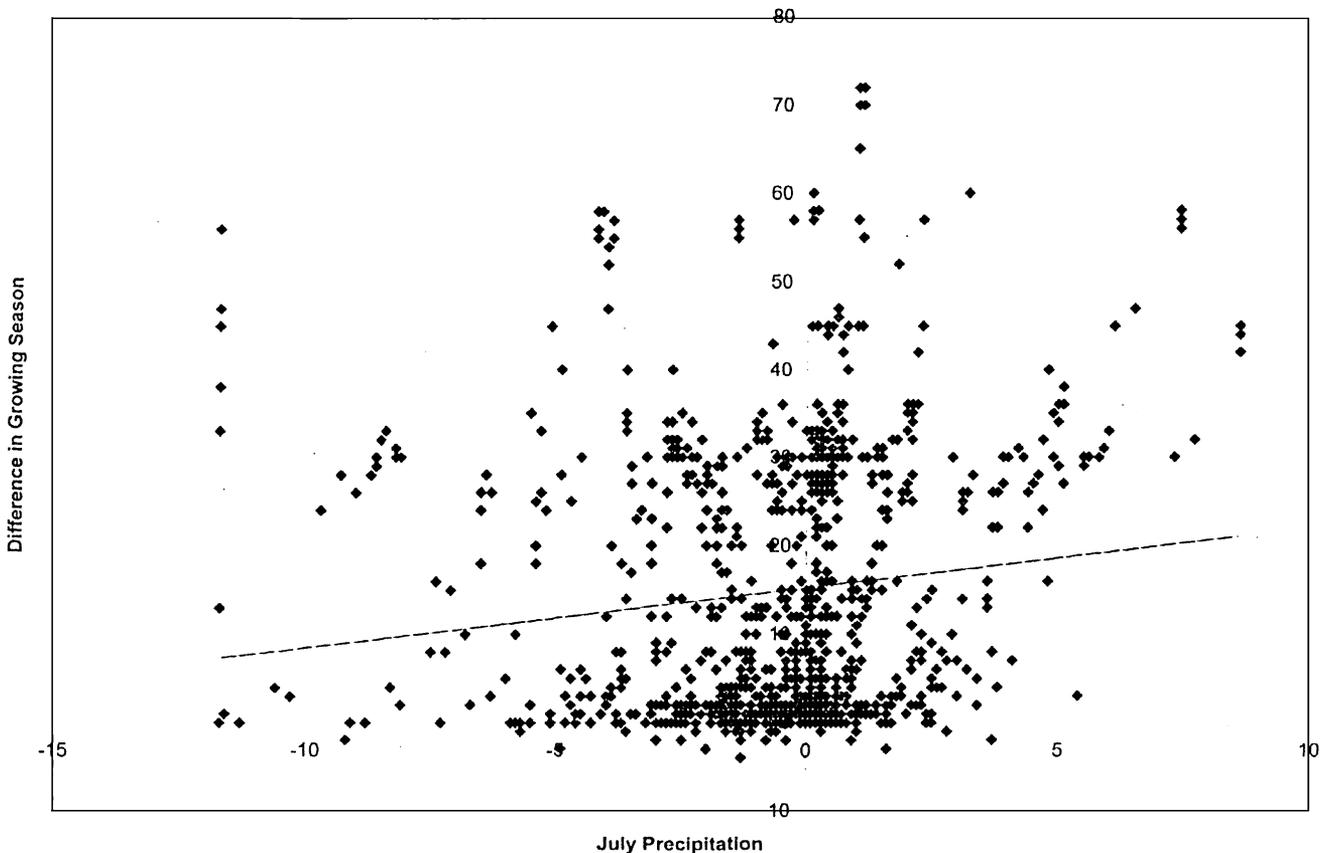


Fig. 6. A scatter plot of July precipitation and growing season length in the year 2100 drawn from the COSMIC exercise.

Fig. 6 meanwhile displays ordered pairs that associate July precipitation (measured in cm) projected for the year 2100 with inferred changes in the length of the growing season (measured as expansions in the size of temperature “hills” of the sort displayed in Fig. 3). Each pair represents the results reported by COSMIC for one of 14 different GCMs given complete coverage of 81 alternative scenarios defined by:

- one of three emissions trajectories (S1, S3 or S7);
- one of three associated sulfate emissions trajectories (high, medium, or low);
- one of three sulfate forcing assumptions ( $-1.2 \text{ W m}^2$ ,  $-0.8 \text{ W m}^2$ , or  $-0.0 \text{ W m}^2$ ); and
- one of three climate sensitivities (1.0, 2.5, or  $4.5^\circ\text{C}$ )

The news is generally favorable on the growing season side, so its implications will be ignored from this point. The news on the precipitation front could, however, be catastrophic; and so attention will be paid to exploring the implications of its range.

Considering the minimum precipitation projected for July from any GCM for each of the 81 alternative

Table 1

Plateau	Maximum precipitation reduction (%)	Precipitation reduction for selected representatives	
		Selection 1 (%)	Selection 2 (%)
One	100–98	– 100	60
Two	75–65	– 80	40
Three	65–75	– 60	40
Four	35–55	– 40	20
Five	20–35	– 40	20
Six	10–20	– 20	n/a

scenarios provided a convenient method for organizing the confusion reflected in Fig. 6. There were, in fact, six collections of similar values that defined “plateaus” of minimum precipitation estimates. The range was staggering; indeed, all showed rainfall declining in the year 2100 anywhere from 100% to roughly 12%. Table 1 identifies the six plateaus in terms of their associated ranges of maximum reduction; but it also notes outcomes that should, by virtue of the application of the selection

## July Plateau # 1

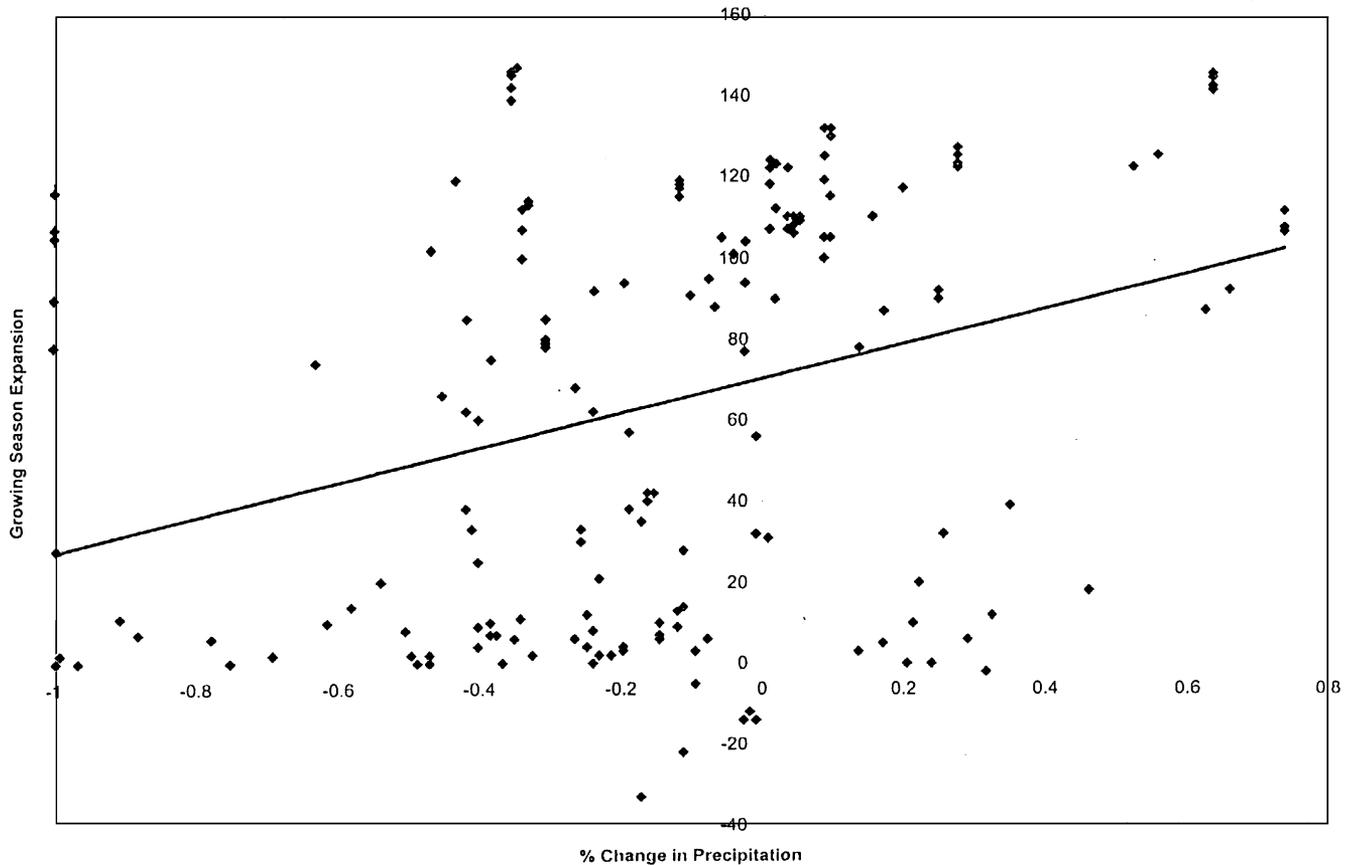


Fig. 7. A scatter plot of July precipitation and growing season length in the year 2100 drawn from first plateau of results from the COSMIC exercise.

procedure outlined in Section 4, be explored more fully. Fig. 7, for example, displays the outcomes of all of the GCM runs for the six scenarios that were grouped in the first plateau. Notice that the distribution rainfall change covers most of the range from  $-100$  to  $+60\%$  fairly evenly. Case 7 from Section 4 would seem to apply, therefore; and so Table 1 targets the two extremes. Similar application of Case 7 and, for the last plateau, Case 3 produced the rest of Table 1. Notice that it suggests running representative groups of scenarios whose July precipitation in the year 2100 are, respectively, 100% lower, 80% lower, 60% lower, 40% lower, 20% lower, 20% higher, 40% higher and 60% higher than the present.

Table 2 identifies combinations of driving variables that can lead the specified GCM's to any of these eight outcome groupings for the year 2100. Fig. 8 displays the transient levels of mean July precipitation for each of these groups; each is drawn from the transient outcomes reported by COSMIC for the GCM/driver combination highlighted by an asterisk in each section of Table 2. Fig. 9 displays times series of the associated sustainability

indices computed for each group by applying the relatively likelihood definition reported in Section 3 to the threshold to mean sensitivity curve portrayed in Panel B of Fig. 5. Notice that traditional maize production would be quite vulnerable over the near-term to climate change if any of the first three groups were to emerge. In each group, more specifically, Fig. 9 reveals that the likelihood of yields falling below 2000 kg per hectare would exceed 50% by 2040 (an by 2030 for Case 1). Groups 4 and 5, meanwhile, display relatively modest reductions in mean July precipitation through 2100; and the sustainability indices for both hold above 60 well into the next century. Finally, Groups 6 through 8 depict the consequences of higher precipitation; the news here is good, with the likelihood of crossing the critical yield threshold falling to almost 10% in Group 8.

Part of the import of Table 2 lies in its support of the transient sustainability indices depicted in Fig. 9. The news can be bad, but it can be good. When? Why? And how is the range of "not-implausible" futures to be judged? These questions remain, and the detail embodied in the diversity (or lack thereof) underlying the groupings

Table 2  
Scenarios that Mimic the Representative(\*) Selections

Fractional Precip Change:						
July	August	Scenario	Sulfate	Forcing	Clim Sen	Model
<b>Group 1</b>						
-1.00	-0.42	S7	H	-1.2	4.5	CCC
-1.00	-0.35	S7	H	-0.8	4.5	CCC(*)
-1.00	-0.20	S7	n/a	0	4.5	CCC
-1.00	-0.27	S7	L	-1.2	4.5	CCC
-1.00	-0.24	S7	L	-0.8	4.5	CCC
-1.00	-0.20	S7	M	-1.2	4.5	CCC
-1.00	-0.20	S7	M	-0.8	4.5	CCC
-0.99	-0.27	S3	H	-1.2	4.5	CCC
-0.97	-0.27	S7	H	-1.2	2.5	CCC
<b>Group 2</b>						
-0.83	-0.13	S3	M	-1.2	4.5	CCC(*)
-0.79	-0.17	S3	M	-0.8	4.5	CCC
-0.79	-0.23	S1	H	-1.2	4.5	CCC
-0.78	-0.62	S7	H	-1.2	4.5	BMRC
<b>Group 3</b>						
-0.63	-0.54	S7	H	-0.8	4.5	BMIRC
-0.62	-0.17	S3	H	-1.2	2.5	CCC
-0.62	-0.18	ST	H	-0.8	4.5	GFQF
-0.61	-0.13	S1	M	-0.8	4.5	CCC(*)
-0.58	-0.25	S7	H	-0.8	4.5	UIUC
-0.57	-0.14	S3	H	-0.8	2.5	CCC
<b>Group 4</b>						
-0.42	-0.33	S1	H	-1.2	4.5	BMRC
-0.42	-0.35	S3	H	-0.8	4.5	BMRC
-0.42	-0.17	S7	M	-1.2	4.5	UILIC
-0.42	-0.07	S7	M	-0.8	4.5	GFQF
-0.41	-0.14	S1	H	-1.2	4.6	GFQF
-0.41	-0.35	S7	H	-0.8	2.5	BMRC
-0.40	-0.12	S3	H	-0.8	4.5	GFQF
-0.40	-0.19	S7	H	-1.2	4.5	OSU(*)
-0.40	-0.35	S7	H	-0.8	4.5	WANG
-0.40	-0.12	S7	H	-0.8	2.5	GFQF
-0.39	-0.18	S1	H	-1.2	4.5	UIUC
-0.39	-0.10	S7	H	-0.8	1	CCC
-0.38	-0.09	S1	M	-1.2	2.5	CCC
-0.38	-0.16	S3	H	-0.8	4.5	UIUC
-0.38	-0.20	S7	H	-1.2	4.5	WASH
-0.38	-0.16	S7	H	-0.8	2.5	UIUC
-0.37	-0.22	S7	H	-1.2	4.5	GFDL
<b>Group 5</b>						
-0.21	-0.12	S1	H	-1.2	4.5	GFDL
-0.21	-0.18	S1	H	-0.8	2.5	8MRC
-0.21	-0.08	S1	M	-0.8	4.5	UIUC
-0.21	-0.18	S3	H	-1.2	2.5	WANG
-0.21	-0.04	S3	M	-0.8	1	CCC
-0.21	-0.01	S3	L	-1.2	4.5	GFQF
-0.21	-0.13	S7	H	-1.2	2.5	GISS
-0.21	-0.06	S7	H	-1.2	2.5	UKMO
-0.21	-0.10	S7	H	-1.2	1	UIUC
-0.21	-0.02	S7	L	-0.8	2.5	GFQF
-0.21	-0.04	S3	n/a	0	1	CCC
-0.21	-0.19	S3	M	-1.2	2.5	SMRC
-0.21	-0.04	S3	n/a	0	1	CCC
-0.21	-0.01	S7	L	-1.2	2.5	GFQF
-0.21	-0.06	S1	H	-1.2	1	CCC
-0.21	-0.10	S1	H	-0.8	2.5	GFQF

Table 2. Continued.

Fractional Precip Change:						
July	August	Scenario	Sulfate	Forcing	Clim Sen	Model
-0.21	-0.07	S3	n/a	0	4.5	UIUC
-0.20	-0.12	S3	H	-1.2	4.5	GISS
-0.20	-0.04	S3	M	-1.2	2.5	GFQF
-0.20	-0.06	S3	L	-1.2	4.5	UIUC
-0.20	-0.00	S3	L	-0.8	4.5	UIUC
-0.20	-0.04	S3	L	-0.8	1	CCC
-0.20	-0.08	S1	H	-0.8	2.5	UIUC
-0.20	-0.05	S3	H	-1.2	4.5	UKMO
-0.20	-0.06	S7	n/a	0	2.5	UIUC(*)
-0.20	-0.25	S7	M	-0.8	4.5	WANG
-0.19	-0.04	S1	H	-0.8	1	CCC
-0.19	-0.03	S3	L	-1.2	1	CCC
-0.19	-0.16	S7	H	-0.8	1	BMRC
-0.19	-0.06	S7	L	-1.2	2.5	UIUC
-0.19	-0.12	S1	H	-1.2	4.5	GISS
-0.19	-0.0e	S1	H	-1.2	4.5	UKMO
-0.19	-0.14	S1	H	-1.2	2.5	WANG
-0.19	-0.19	S3	M	-0.8	2.5	SMRC
-0.19	-0.12	S7	H	-0.8	4.5	GISS
-0.19	-0.02	S7	H	-0.8	4.6	UKMO
-0.19	-0.06	S7	L	-0.8	2.5	UIUC
<b>Group 6</b>						
0.19	-0.12	S3	L	-0.8	4.5	HEND
0.19	0.42	S7	M	-1.2	1	GF30
0.19	-0.12	S7	L	-1.2	2.5	HEND
0.19	0.68	S7	L	-0.8	1	POLL
0.20	0.62	S1	n/a	0	2.5	POLL
0.20	-0.11	S3	L	-1.2	4.5	HEND
0.20	-0.23	S7	M	-0.8	4.5	HEND
0.20	0.42	S7	M	-0.8	1	GF30
0.20	0.44	S1	M	-0.8	2.5	GF30(*)
0.21	0.58	S3	H	-0.8	2.5	GF30
0.21	0.62	S1	L	-0.8	2.5	POLL
0.21	0.81	S7	H	-1.2	2.5	GF30
0.21	0.67	S1	H	-0.8	4.5	GF30
0.21	0.63	S1	L	-1.2	2.5	POLL
0.21	0.79	S3	M	-1.2	2.6	POLL
0.21	1.76	S7	H	-1.2	4.5	POLL
0.21	0.43	S7	n/a	0	1	GF30
0.21	0.43	S7	L	-0.8	1	GF30
0.21	0.43	S7	L	0	1	GF30
0.22	1.18	S7	H	-0.8	2.6	POLL
0.22	0.43	S7	L	-1.2	1	GF30
<b>Group 7</b>						
0.38	0.76	S1	L	-0.8	4.5	GF30
0.39	0.77	S1	L	-1.2	4.5	GF30
0.40	0.92	S7	M	-1.2	2.5	GF30(*)
0.40	1.27	S7	n/a	0	2.5	POLL
0.41	0.96	S3	M	-1.2	4.5	GF30
0.41	1.28	S7	L	-0.8	2.5	POLL
0.42	1.02	S1	L	-1.2	4.5	POLL
0.42	1.28	S7	L	-1.2	2.5	POLL
<b>Group 8</b>						
0.68	1.94	S7	M	-0.8	4.6	POLL
0.62	1.42	S7	M	-1.2	4.5	GF30(*)
0.63	1.98	S7	n/a	0	4.5	POLL
0.03	1.96	S7	L	-1.2	4.5	POLL
0.63	1.98	S7	L	-0.8	4.5	POLL

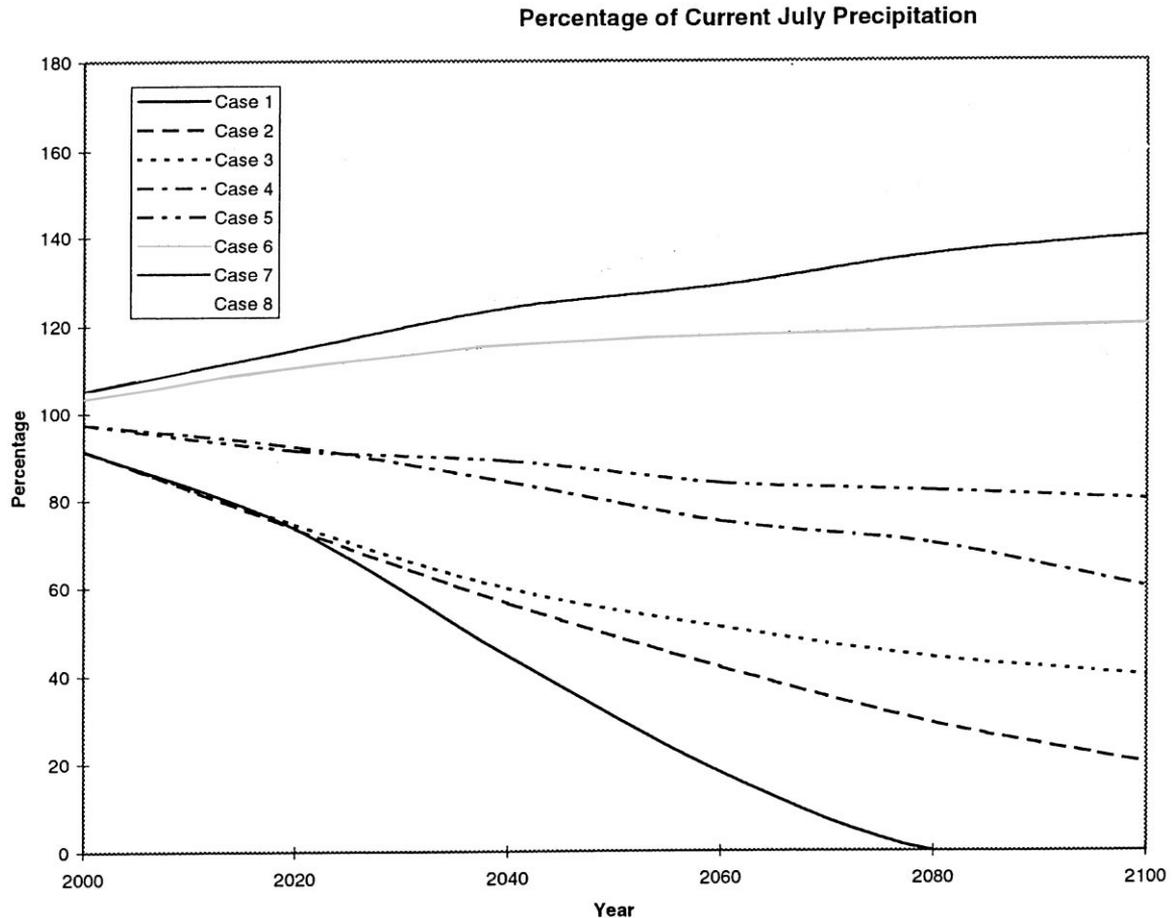


Fig. 8. Trajectories of July precipitation for eight selected “not-improbable” future scenarios.

recorded in Table 2 produce can speak even more emphatically to each. Notice, for example, that extreme changes in precipitation are generally the result of pushing extreme emission trajectories through selected GCMs with high climate sensitivity, regardless of the direction of that change. This observation is supported graphically by Panels A and B of Fig. 10 in which the combinations of emission scenarios and climate sensitivity required to support the representative precipitation trajectories for Groups 1 and 8 are displayed. Note, as well, that extreme changes in precipitation seem to be artifacts of particular GCMs – the CCC Model of the Canadian Centre for Climate Research on the low side and the POLLD and GF30 Models of Pollard and Thompson and the Geophysics Fluid Dynamics Laboratory, respectively, on the high side. Careful examination of exactly how these models produce such dramatic declines or increases in precipitation for Mexico would certainly be a warranted next step in a more careful examination of vulnerability.

Finally, it is important to note that changes in precipitation ranging between plus or minus 20% of current

levels can be sustained by a large number of models driven by emission scenarios that cover the “not-improbable” range with nearly any degree of climate sensitivity. Panels C and D of Fig. 10 display combinations of emission scenarios and climate sensitivity that support the representatives of Groups 5 and 6. These panels, and the diversity of associated GCM’s reported in Table 2, underscore a robustness that is, at the same time, encouraging and unsettling. It is encouraging because the future would not portend disaster in any of these cases; but it is unsettling because there are no obvious “footprints” that could be detected among the driving variables that would help planners to foresee even the direction of change in precipitation.

## 6. Preliminary consideration of a government-supported adaptive strategy

Eakin (1999) highlights an experimental program of switching to draught-resistant maize hybrids that has

## Sustainability Index for Traditional Maize Agriculture

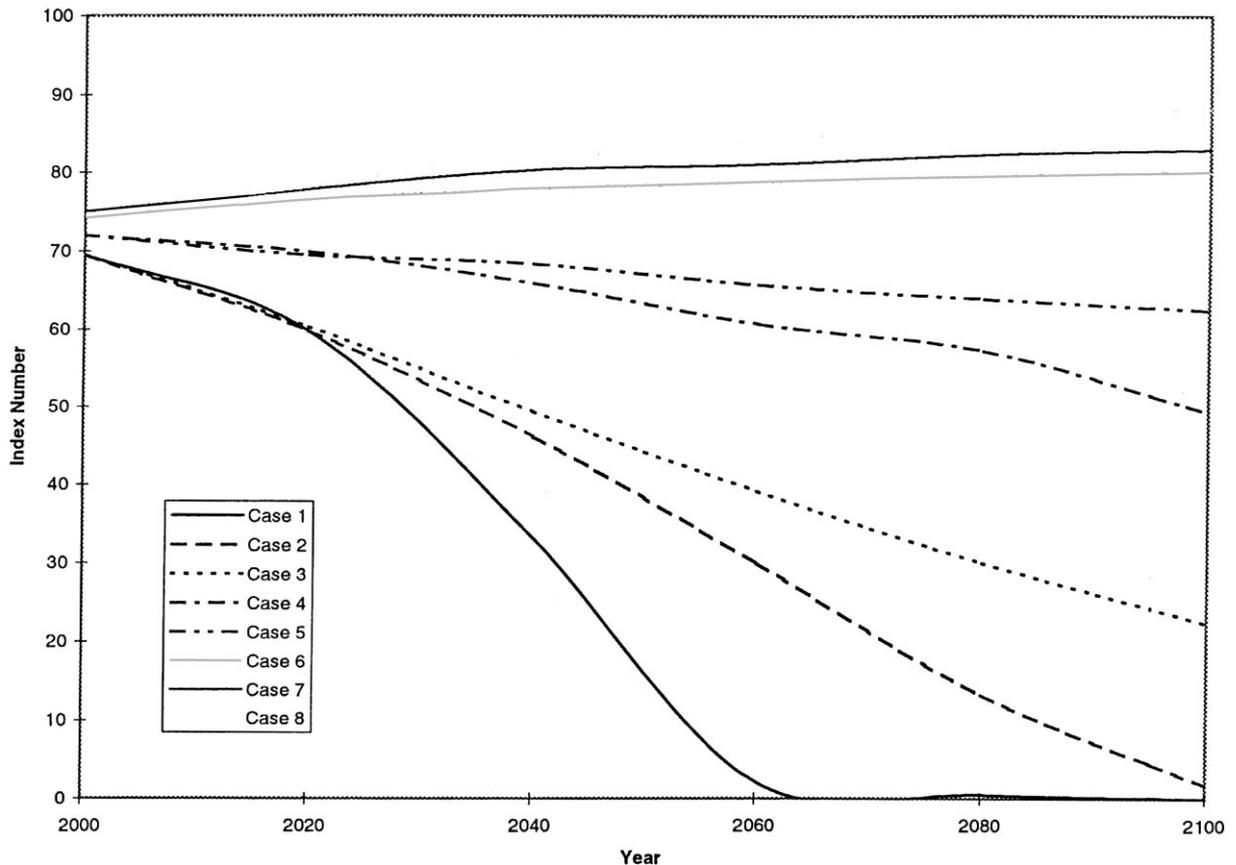


Fig. 9. Corresponding trajectories of the sustainability index for traditional maize agriculture for eight selected “not-implausible” future scenarios.

been underway for the past 20 years or so. She reports that yields derived from these hybrids have not been significantly larger during the most severe draught years; but her Fig. 2 does reveal that yields have, otherwise, exceeded the traditional methods examined above. Indeed, the likelihood that yields will fall below the critical 2000 kg/hectare threshold is approximately 15% for the hybrids (down from the nearly 30% frequency experienced by traditional farmers). Fig. 11 displays transient series of sustainability that were derived by calibrating the method to accommodate this new information for two of the five representative cases in which July precipitation fell. Notice that each path starts higher than before. Case 2 still sees sustainability falling below 50%, but over a longer time horizon. Indeed, even Case 2 does not reproduce the current sustainability of roughly 70% until well into the next century. Case 4, meanwhile, actually holds above the 70% benchmark throughout the century.

The potential for productive adaptation exists, but the case is far from overwhelming. Eakin notes that switch-

ing to the hybrids increases costs, and she offers a discouraging evaluation of hybrids because their performance during severe draught is not any better than the traditional methods. Still, a comparison of the transient sustainability indices displayed in Fig. 11 suggests that switching could improve conditions in the more marginal years when precipitation falls only moderately below the mean. Which observation might dominate in a careful analysis of the relative merits of switching to the hybrid varieties and under what conditions might this dominance be most robust? Only a more detailed examination of the relative value of switching along paths of moderate precipitation decline (and even severe decline if word that the CCC Model results are not impossible is not forthcoming) will tell.

## 7. Concluding remarks

Purists will object to the procedure offered here because it is not precise; perhaps it is not even scientific.

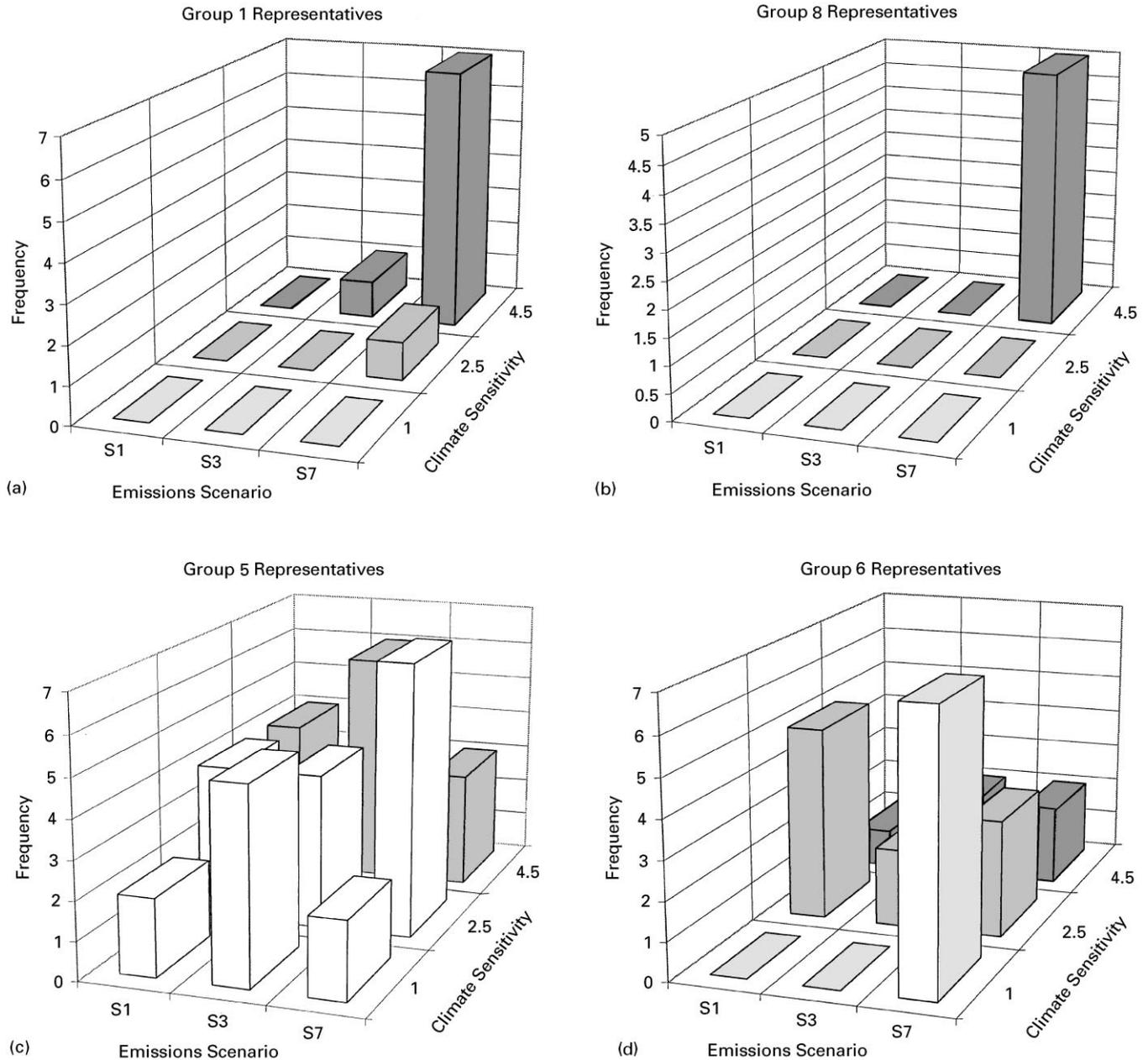


Fig. 10. Frequency distributions of climate sensitivity and emissions consistent with representative sustainability scenarios; Panels A through D depict the distributions for two extreme groupings (Groups 1 and 8) and two middle groupings (Groups 5 and 6), respectively.

No claim of precision was made, however. Indeed, the procedure is offered only as a means of moving forward reasonably before uncertainty is resolved because (1) some uncertainty will never be resolved and (2) work on impacts *cum* adaptation cannot wait any longer to begin the process of assessing relative vulnerabilities to climate change and climate variability. Many others will object to the way COSMIC deduces country specific trajectories for critical impact variables from the coarse varied scales of GCM results; but it will, again, be quite a while before GCM resolution will improve. COSMIC

does, however, offer “not implausible” values for many impact variables; and surveying across multiple GCM’s to select representatives of “not implausible” ranges will be totally misleading only if all of the global circulation modelers are doing something wrong. The procedure described here therefore holds the promise of identifying areas and systems for which detailed analysis of adaptation will pay the largest dividends *and* giving these analyses a small set of impact alternatives that span a large portion of the range of “not implausible” futures and high consequence thresholds.

## Sustainability - Traditional and Reform Practices

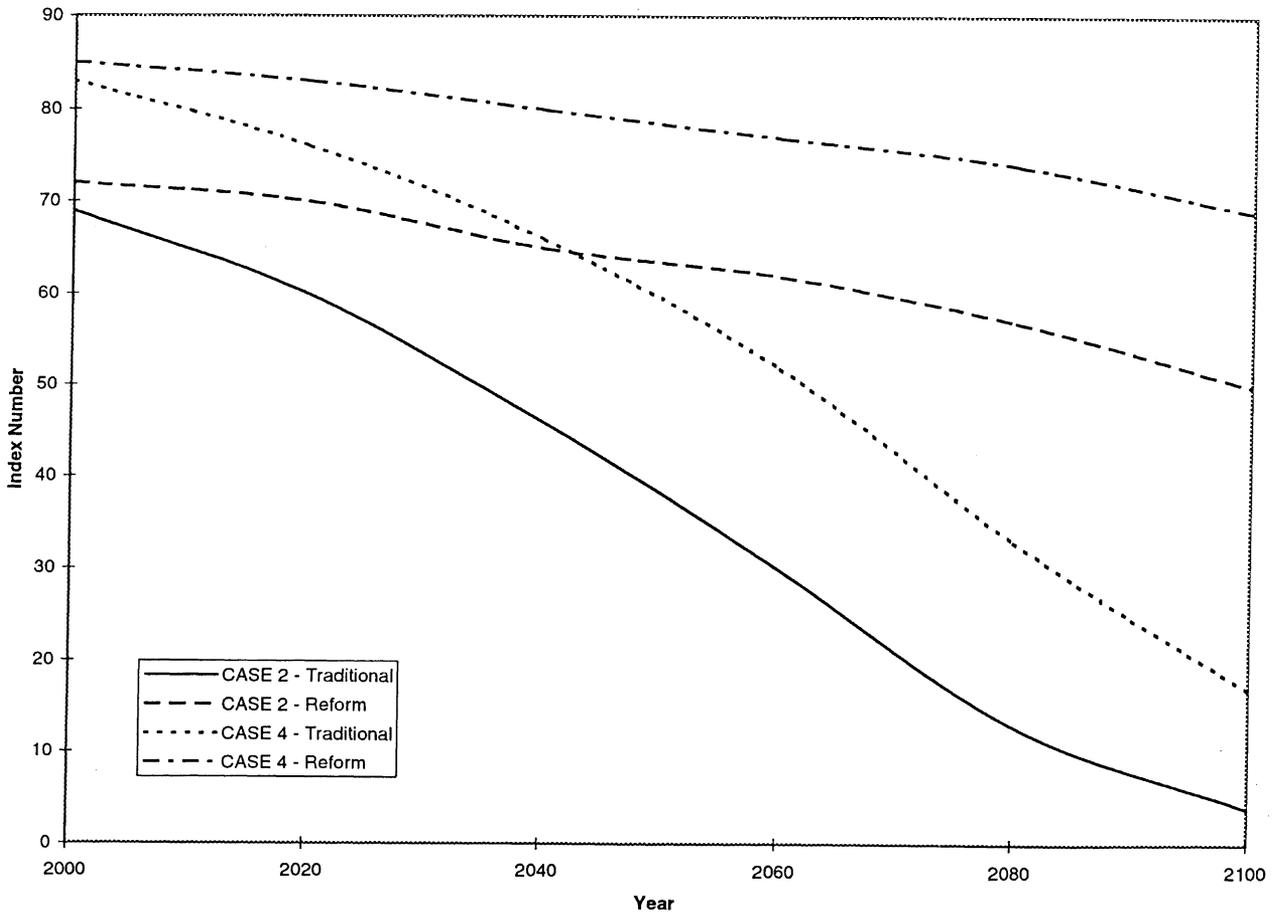


Fig. 11. The sustainability trajectories for traditional and reformed maize practices along two representative scenarios.

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