ADAPTATION AND THE GUARDRAIL APPROACH TO TOLERABLE CLIMATE CHANGE

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Abstract. Windows delineating tolerable or "acceptable" conditions associated with climate change can be defined in terms of a variety of parameters; a preliminary window offered by the Scientific Advisory Council on Global Change of the Federal Government of Germany sets limits on temperature change and the rate of temperature change. Investment in adaptation can alter the size and shape of these windows, and different emissions trajectories are associated with different limiting points on their boundaries. As a result, the value of adaptation depends upon both the underlying structure of the tolerable window and the basecase emissions trajectory. Given uncertainty about both, the best near-term policy should be cast in a sequential decision-making framework. Seen in this light, improved adaptive potential can either reduce the cost of sustaining tolerable climate change or increase the opportunity cost of holding to more restrictive boundaries.

1. Introduction

It is becoming increasingly evident that adaptation can dramatically reduce the imputed cost of climate change and thus the economic benefit to its mitigation. Estimates of the economic vulnerability of developed property along the United States coastline to greenhouse-induced sea level rise published by Yohe (1990) are, for example, nearly ten-times larger than exactly analogous estimates of economic cost derived from market-based adaptation reported by Yohe, et al. (1996) and Yohe and Schlesinger (1998). Similar comparisons in other sectors of developed economies may not be as large, of course; and the distinction between vulnerability and cost may have no significance at all for non-market economies or nor-market sectors. Even in coastal zones, questions about the roles of storms, insurance coverage, political power and imperfect information in hampering the efficiency of the market-based adaptation have not been fully explored. These caveats notwithstanding, though, the potential for making serious errors in judging the benefit side of any dynamic cost-benefit consideration based solely on vulnerability is clear because adaptation will, in most if not all cases, play a central role.

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Responding in part to this observation and in part to the anticipated difficulty (if not impossibility) of capturing a complete list of feasible future adaptive options along uncertain trajectories of future climate change in a credible dynamic cost-benefit framework, several researchers have begun to experiment with alternative methods of evaluating mitigation strategies. Schellnhuber and Yohe (1997) mention two:

(1) an iterative approach where institutions are designed to administer a series of robust near-term mitigation strategies that evolve over time as new information about impacts and damages emerge, and

(2) a guardrail approach that searches for cost-effective mitigation strategies that are designed to keep the future from venturing too close to evolving definitions of the boundaries of truly dangerous climate change along multiple dimensions.

They conclude that a creative synthesis of these two approaches could easily dominate either the potentially fruitless search for a forward-looking policy trajectory that solves the full-blown dynamic cost-benefit optimization problem posed by more conventional integrated assessments *or* the simplistic specification of long-term emissions targets and timetables however administered.

Even though they do not require intertemporal dynamic optimization in which researchers are obliged to express all impacts in terms of currency, neither of these approaches buys much in the way of increased simplicity. The confounding truth is that adaptation should also play an important role in the specification of the guardrails, their evolution over time, and the incorporation of that evolution into effective and efficient iterative response strategies. This paper is designed to begin an exploration of that role. It will rely on some relatively abstract models of global change, but it will make several qualitative points whose significance are not linked inexorably to the specifics of either the model or the numerical results. First, the definition of the guardrails that define "tolerable" risk can make an enormous difference. Equivalent definitions of tolerable change can extend or diminish the time available for responding to new or more clearly understood old threats by decades. Secondly, the limits of tolerable change may be defined simultaneously along many dimensions (like temperature change, the rate of temperature change, levels of precipitation in particular months, correlations of precipitation patterns across months, and so on). In this case, increasing the potential to adapt in one dimension can create flexibility in other dimensions and thereby diminish the need for stringent mitigation. In other circumstances, though, increased adaptive potential can have no effect because it would work on a non-binding portion of a boundary that is dominated by some other definition of tolerance. Thirdly, adaptation can have an enormous effect on the cost of implementing even an iterative policy that tries to avoid contacting guardrails that change over time. Even small changes in response options can increase or reduce costs by hundreds of billions of dollars (in terms of expected present value). Finally, adaptation does not just happen. It requires the creation and dissemination of credible new information, and so research across the full range of adaptive options is really a policy variable. Targeting research where it might do the most good can pay enormous dividends. Focusing effort elsewhere can be enormously expensive. It may be prudent, therefore, to give serious consideration to enacting short-term policies that have been shown to be more productive in eliciting information from complicated systems even if they are less cost effective in terms of what they might actually achieve. Reilly and Schimmelpfennig (this issue) make this point explicitly.

These lessons will be drawn from discussions that begin in Section 2 with a chronology of the recent development the specific underpinnings of climate guardrails embodied in the “tolerable window approach” of the Scientific Advisory Council on Global Change to the Federal Government of Germany (the WBGU). Section 3 illustrates, using sea level rise, the simple point that incorporating adaptation into the definition of “tolerable” climate change can be critically important in determining the cost of meeting the reduction target. Section 4 highlights the sensitivity of defining “tolerable change” to the future course of emissions and thus to the economic drivers of climate change. Section 5 finally examines briefly the value of exploiting the tradeoff in adaptive potential across the multiple dimensions of tolerable change; and Section 6 highlights some important lessons.

2. Illustrating the Guardrail Approach - Tolerable Windows of Global Change

Integrated assessments that move forward from cause to effect have proven to be very useful in producing simulations that have framed much of the policy debate thus far [see, e.g., Nordhaus (1994), Manne, et al. (1995), etc.] Subject to informational limitations, these direct approaches are quite simply well-suited by design to assess the environmental and socioeconomic consequences of various emission reductions strategies. They are, however, increasingly less appropriate in searching for policies in the practical decision-making arena where the objective seems to be one of finding the best strategy to reach an environmental or impact objective according to criteria that may not be entirely economic in character. Policymakers want to know, for example, about the magnitude and kind of climate change that might produce undesirable impacts in order to put appropriate policies in place. Indeed, Article 2 of the Framework Convention on Climate Change, the most important political document on the issue so far, invokes this requirement. It calls for the need "to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Framing the central question for climate policy this way, several practical questions follow immediately:

(1) What defines a dangerous level of interference with the climate system, especially when human beings can adapt to the consequences of this interference?
(2) At what level should greenhouse gas concentrations be stabilized to avoid those dangers?
(3) What emission trajectory optimally achieves stabilization at the appropriate target?

These questions have given rise to a new family of analyses that start from the damage/impact side and proceed backwards; the family has been dubbed "inverse assessment".

Working Group I of the Second Assessment Report prepared by the Intergovernmental Panel on Climate Change [IPCC (1996)] took a first step in responding to these questions by developing emission paths leading to stabilization of atmospheric concentrations of greenhouse gases at various levels. Wigley, Richels, and Edmonds subsequently defined a set of alternative emission paths (dubbed "WRE" paths) that lead to the same stabilization levels in concentrations but involved slightly different total emission budgets and, more importantly, different time schedules of actual emission reductions (Wigley et al., 1996a). Wigley and his colleagues have shown that these alternative paths achieve the same long-term environmental objective as those of IPCC WGI at a much lower cost. Debate still rages about the interim implications of the alternative WRE paths and how short-term policy measures might be designed to guarantee downstream compliance. Answers to these questions are less important for present purposes than the simple observation that it is not a cost-benefit debate; it is, instead, one of policy design for *a specific set of policy objectives;* and so it follows that care should be taken in defining those objectives.

Taking the "inverse assessment" approach one step further toward defining what constitutes a dangerous change in the climate, the WBGU defined climate protection targets in physical terms [see WBGU (1995a)]. In short, the basic principles from which the WBGU targets were drawn were two in number: (i) preserving the creation and (ii) avoiding unacceptable costs. The first principle lead to a review of the breadth of temperature variability in the late Quarternary - the geological period shaped our today's environment. It was defined on the low side by an estimated global mean temperature in the Wuerm ice age of 10.4° C and on the high side in the Eamian of 16.1° C. The WBGU argued that moving significantly outside of this temperature range would imply major changes in the composition and function of today's ecosystems. Expanding the derivative tolerance domain by 0.5° C at each end, WBGU saw a tolerable temperature window ranging from 9.9° to 16.6° C. Since the global mean temperature today is 15.3° C, this range translated into constraining additional warming to 1.3° C.

The Council meanwhile took their second principle to mean, in practical terms, that the maximum tolerable loss to the global society due to climate change was 5 percent of gross world product (GWP). Most studies estimate global annual climate damages attributable to a CO_2 doubling through the end of the next century at 1-2 percent of GWP. The model adopted by the Council showed that such a pace would be sustained by a 0.2° C increase in global mean temperature per decade. Moreover, all of the underlying damage estimates excluded extreme events (drought, floods, tornadoes) and possible synergistic effects of different global change trends. Considering these events as well, it appears to be realistic to assume that 0.2° C per decade pace of temperature change would correspond to the tolerable upper limit in terms of adaptation and damage costs on the order of 5 percent of the global GWP. Finally, the Council noted that adaptive capacity declines as we approach the boundaries of the tolerable temperature window. As a result, the rate of change in temperature along any emissions trajectory near the limits of tolerable change should decline ultimately to zero.

Figure 1 reflects these constraints in what has become known as a "the WBGU tolerable window" for climate change. Notice that the level and rate constraints interact at their extremes to "round off" what would otherwise have been a rectangular constraint. The notion is that systems' tolerance to the rate of change declines as the change grows. While systems might be able to tolerate 0.2° C per decade increases in temperature in the near future (after a 1.0° C warming from pre-industrial times), they would not be able to handle the same pace in the more distant future when the environment would be that much warmer. The WBGU then argued for a "backward mode" of computation. Having considered the impacts of climate change on mankind and nature and defining a "window" of "tolerable" future climate change, the inverse calculation would identify (all) global emission paths that would keep climate within the prescribed window and thus the minimum requirements for a global emission reduction strategy.

Several points should be emphasized at this point. Tolerable climate windows (perhaps defined in terms that extend well beyond temperature change and the rate of temperature change) will have to be derived from climate impact response functions. Work is underway to uncover these functions for various important sectors. Absent the results of that work, however, we take the WBGU window as a reference point for our analysis even though our understanding of some of the physiological principles that underlie its definition do not allow much room for adaptation. As a result, a clear distinction needs to be made between the TWA as a decision-making tool and the specific WBGU window upon which we will focus our attention. TWA is being developed as an analytical tool with many purposes: to check the feasibility of multiple environmental objectives, to derive a set of control paths consistent with those objectives, and to evaluate the opportunity cost of allowing the most restrictive objectives to define the limits of tolerable change. The results reported here will address the third of these tasks most directly.

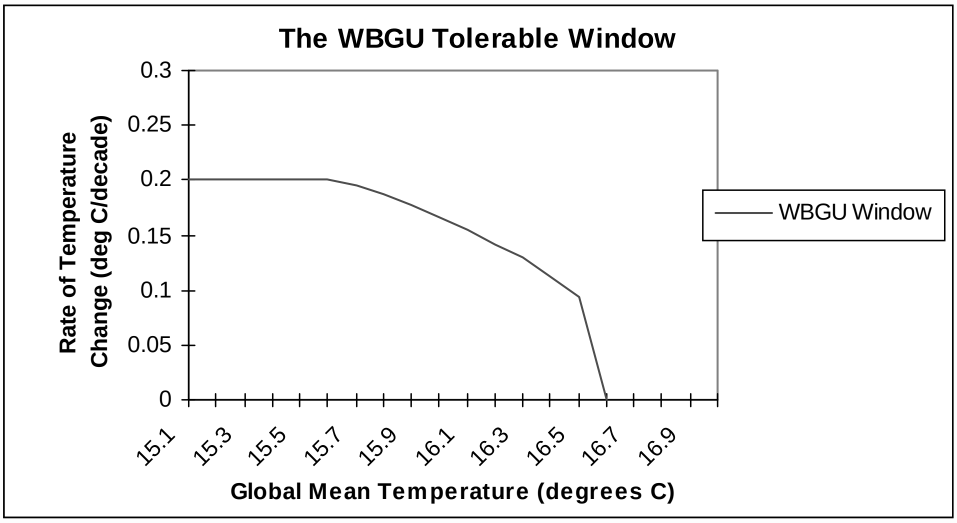

Figure 1. A sample representation of a tolerable window drawn by the WBGU.

The TWA is, in support of each of these tasks, designed specifically to separate scientific analyses (building the best available knowledge into climate change models) from normative decisions (specifying what is "dangerous", what is "acceptable", and/or what is "tolerable"). The fundamental notion that framed its creation is that the determination of what is and is not tolerable will always be a social decision problem regardless of the state of scientific knowledge. It takes as given that we cannot expect that the boundaries of a "tolerable window" will be defined purely on the basis of that knowledge. In addition, the reports of the WBGU that adopted the TWA broadly defined are not scientific publications. The Council is a scientific advisory board whose task it is to give policy advice to the federal government of Germany. The Council therefore articulates policy positions, based on its reading of scientific publications and the insights of its members; and so its work reflects the normative judgments of its members based on scientific understanding seen through the filters of ethically-based positions. Given the enormous uncertainties of the climate change issue, the Council has, in short, offered normative definitions of dangerous and thus unacceptable change based on its perception of risk and the degree to which it is willing to accept or avoid that perceived threat.

How certain can we be that any such window is an appropriate target for climate change policy? That is still an open question; and adaptation will play a large role in uncovering the answer. In Annex I of the English version (WBGU 1995b), the Council recalled the "first principles" from which the climate window is derived. They reconfirmed that allowing the climate to change beyond its boundaries would imply global climatic conditions "deviating markedly from those that have shaped the coevolution of humanity and ecosphere..." (p 26). The Council also remarked "that various assumptions about the climate damage function ... are mere *educated guesses*" (original emphasis), especially as far as the relationship between the degree and rate of temperature change is concerned "(p 32). This Annex also contained hints about more specific justification of constraints on temperature gradients by pointing to the work of the German Enquete Commission [EK (1994)]. Indeed, the Council quoted EK (1994): "Ecosystems would probably have major difficulties adapting to temperature gradients of more than 0.1 C per decade" [WBGU (1995b), p 32). Assuming that the elasticity of natural systems in the center of the window is twice as big as normally assumed, then 0.2° C per decade constraint was thought to be a rather optimistic medium-term preservation objective.

The 1995 Annual Report (WBGU 1996a) incorporated WBGU (1995a) with only one major modification in interpretation. No additional information was provided about the various assumptions from which the climate window was drawn. The English version of the 1995 Annual Report (WBGU 1996b) contained WBGU (1995b) with only minor changes. The one difference of note offered an extended explanation of limiting the rate of temperature change. The Council declared in the 1995 Report that, when considering all simple yet non-trivial aspects of the problem, the upper limit of 0.2° C per decade for the rate of temperature change "is not overly pessimistic: inside the admissible temperature window, a temperature gradient of 0.2 C per decade would actually cause adaptation costs of up to 5 % of gross state product annually" (WBGU 1996b: 205). The mention of adaptation cost represented an initial recognition of a tension between ecosystems and human systems. If these two types of systems are different in their abilities to adapt, then their role in defining the limits of tolerable climate change could diverge.

In its study for the Third Conference of the Parties of the Framework Convention on Climate Change (FCCC), the Council [WBGU (1997a) and WBGU (1997b)] again adopted the TWA. Their objective was, by then, to characterize "maneuvering room" for climate change and climate policy for the next 200 years by normatively specifying *ecological, economic and social constraints* that simply should not be exceeded. The combination of these constraints defined a workable tolerable window for climate protection (WBGU 1997a, p3). The Council noted that, despite numerous climate impact studies "it is extremely difficult to assess adaptive capacities of ecosystems and socioeconomic systems in terms of Article 2" of the FCCC [WBGU (1997a), p10] because climate impact assessments require higher spatial and temporal resolution than is currently available. Moreover, any amount of future climate change could lead to surprising transformations due to nonlinearities in the climate system.

Figure 2 illustrates the underlying structure for a window drawn from these sorts of multiple considerations. The original window of Figure 1 is again represented, but it is shown to be the intersection of (in this case) three different constraints that might reflect the climate sensitivity of three different sectors or systems:

(1) Constraint A that displays intolerance to climate change proceeding faster than roughly 0.2° C per decade (a system whose pace of migration toward cooler temperatures is limited, e.g.);

(2) Constraint B that displays intolerance to global mean temperatures higher that 16.6° C (a system that cannot migrate and cannot survive temperatures in excess of a specified maximum, e.g.); and

(3) Constraint C that displays intolerance to combinations of temperature and the pace of temperature change (a more complex system whose tolerance in both dimensions is negatively correlated, e.g.).

The window portrayed in Figure 1 clearly lies below Constraint A, to the left of Constraint B, and below Constraint C in Figure 2. This underlying structure, drawn from multiple sources, can play a critical role when discussions turn to allocating scarce research resources to exploring adaptive potentials across various sectors.

More recent versions of windows in the TWA-based analyses [e.g., the ICLIPS analysis reported in Toth, et al. (1998)] have made this last point defining limits for maximum tolerable SLR. The main source of information for defining the SLR window is Rijsberman and Swart (1990). Their report suggests that targets could "be based on either, or both, the impacts of SLR on vulnerable natural ecosystems such as coastal wetlands or coral reefs, or the impacts on human systems, varying from small island nations to some of the world's largest cities situated on the coast" (p.22). Again reflecting a growing tension between ecosystems and human systems, Rijsberman and Swart recommended targets for SLR range between 20 and 50 cm above 1990 level for the magnitude and between 2 and 5 cm/decade for the rate. They argued that 2 cm/decade would permit the vast majority of ecosystems to adapt while damage would rise rapidly beyond this rate. They also concluded that a total of 20 cm SLR would imply some storm damage along the coast while 50 cm of sea level rise would leave some, but certainly not all, small islands under water (p. viii). Within these intervals, then, they proposed 30 cm as maximum tolerable SLR and specified a limiting rate of 3 cm/decade to reflect modestly conservative judgments of the limits of tolerable change. It is important to emphasize that, just as in the case of the temperature constraint definitions, there is no direct tangible evidence to support these limits.

When the discussion of TWA's moves beyond the conceptual WBGU context into this more general level, the multiple support constraints that underlie any window of the sort displayed in Figure 2 can become a source of complexity when adaptive options are considered. To see how, it is important to recognize that errors in the specification of any support constraint may (but may not) distort the ultimate target window and that the result might mean that more or less mitigation will be required. Suppose, for example, that Constraint B were to shift to the left and thereby reduce the tolerable limit to temperature change; obviously the target window would shrink accordingly and more mitigation should be contemplated. If, by way of contrast, more tolerance to the rate of temperature change were discovered so that Constraint A could shift up, then there would be little effect on the size of the target window (and thus on the appropriate level of mitigation) because Constraint C would still bind. Finally, if the temperature change endpoint of a correlated constraint like C were to climb, then the target window could expand by offering *higher maximum rates of temperature change* ***as well as*** *higher maximum temperatures*. This dual benefit is the product of correlated effects that should not be forgotten when mitigation responses are considered. In any of these cases, though, it is important to note that expanding the window of tolerable change can diminish and expand both the need for mitigation and the flexibility of its design in ways that are not necessarily straightforward or consistent. Searching for an appropriate mitigation strategy to achieve any window can be likened to

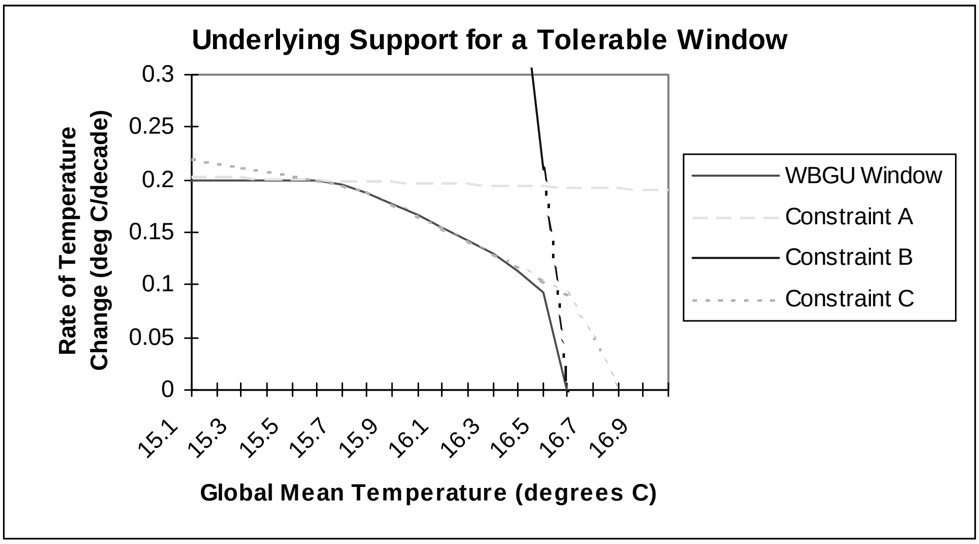

Figure 2. Representative constraints that support the definition of any tolerable window.

searching for trees above a certain height in a forest. Diminishing (or expanding, for that matter) the area of the forest can make the search more difficult (or less difficult) if the marginal area is home to many tall trees, but it might have no effect at all if the marginal area is home to only very short species.

In light of this complicated interface between adaptation and the mitigation required to keep climate change “tolerable”, it is especially important to recognize that the TWA does not imply an absolute priority for environmental protection over economic and social objectives. The Council has always held that the acceptability of climate protection strategies was also an important constraint. The TWA requires explicit specification of normative statements, does not convert environmental and other non-market damages into monetary units, does not balance future damages against present damages, and does not allow compensation of benefits does not convert and damages across arbitrary impact categories (e.g., life-sustaining resources and/or recreationally valuable regions). By specifying the climate window on the basis of geohistorical considerations, the Council continued to hold that the climate window defined in its 1995 report was appropriate in terms of "preventing dangerous climate change" in the spirit of Article 2 of FCCC. The Council nevertheless pointed out that these constraints were still very crude and that it was hardly possible to define a global, time-independent maximum burden level anyway. In addition, the Council indicated that its global climate window was deliberately chosen to be *large*. Indeed, the Council quoted reports by two Enquette Commissions of the German Parliament declaring that healthy vegetation are just able to keep up with 0.1 C per decade warming.

The Council was also not alone in adopting an inverse approach. Citing its own earlier work [(EK (1991)], for example, the Enquette Kommission defined objectives for climate protection that were similar to the WBGU climate window. They set an upper limit for global mean temperature increase of 2° C by 2100 over 1860 so that humans would not enter a climate regime that they had never experienced. They also prescribed a maximum rate of global mean temperature increase of 0.1° C per decade between 1980 and 2100 because this was the fastest pace, according to current knowledge, that natural ecosystems could tolerate [EK (1994), p 59]. The basic argument for limiting the rate of temperature change was based on the assumed maximum rate of migration of natural ecosystem, especially northern forests.

Although it has played a relatively smaller role in studies conducted with the TWA-based models so far, the breadth and the shape of the emissions corridors can be employed to explore tolerable rates of abatement. The Council admitted the difficulties involved in estimating abatement cost functions and the presumably large differences in marginal abatement costs across nations and economic sectors [WBGU (1997b)]. It has assumed, however, that it should be possible to reduce global GHG emissions at 2 percent per year "without major economic side effects" in industrial countries. By taking advantage of lower marginal abatement costs in developing countries, this rate could be as high as 4 percent per year for shorter periods.

Figure 3 loosely replicates Figure 14 in Toth, et al. (1998). It displays a typical time series of ordered pairs of temperature change and temperature change rate along a cost minimizing mitigation trajectory produced by Alan Manne and his associates from their MERGE model. It begins with current conditions represented by the point that lies within the window at the very left of the locus. The locus then proceeds to the right and eventually down as the future unfolds. Notice that the static window constrains the locus twice - once in the relatively near-term when the locus hits the boundary of the window in the strictly positive quadrant and again along the horizontal axis after the pace of temperature change has fallen dramatically. The endpoint is, in fact, representative of all time after the maximum allowable temperature has been achieved and must be sustained by no further increases in temperature (and so a zero rate of change). It is also important to note that taking these limits too seriously would be very misleading. None of the values identified thus far represent sharp edges of cliffs beyond which major disasters can be taken as certain. The main value of TWA-based results is to clarify relationships between perceived levels of tolerance of various human systems and ecological systems and to explore the broad allowances for anthropogenic emissions to prevent exceeding them.

We now turn to examine the role of the adaptive capacity of human systems in the overall definition of tolerance. In so doing, the tension between the respective abilities of human and ecological systems to adapt will come into play. Figure 4, for example, builds on the implications of Figure 2. It displays one extreme case in which ecologically based limits of tolerable change drawn from the historical record [represented by locus ABC in the figure] define the boundaries of tolerable change because they are more binding than analogous limits drawn from human systems [locus A'B'C']. If human systems can adapt while ecological constraints continue to be defined by historical precedent, then the A'B'C' locus could move up and/or to the right more with no effect on the size of the actual window of tolerable change. The ecologically based locus would still be binding, in this case, and estimates of the reduction in the mitigation cost (net of adaptation costs) required to stay within the growing A'B'C' that would represent increases in the opportunity cost of staying within the smaller, ecologically based window, instead. If Figure 4 displayed the opposite case in which human systems'

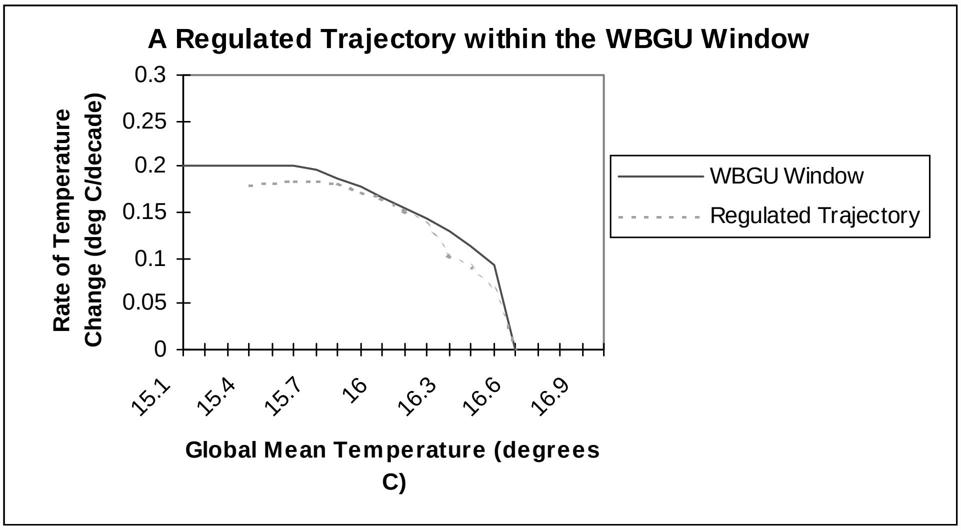

Figure 3. A representative time series of temperature change and rate of temperature change that satisfies the WBGU window.

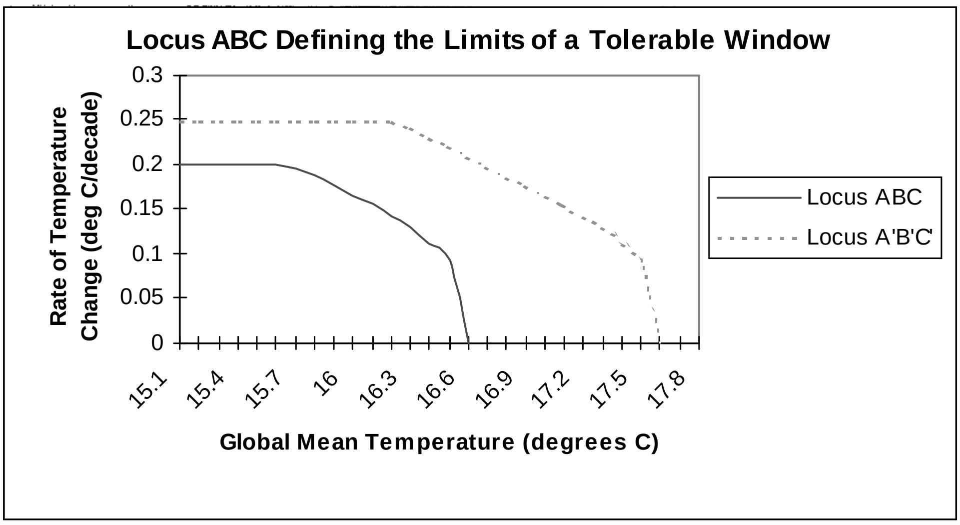

Figure 4. An alternative representation of window support from two underlying loci.

boundaries were initially more binding, though, then adaptive responses would then move the ABC locus up and/or to the right would actually enlarge the target window. As a result, society could expect to glean the benefit of the corresponding reductions in mitigation cost if they outweigh the cost of adaptation without reference to the ecological consequences.

The work reported here will focus on the potential ramifications of adaptation by human systems in quantifying the limits of tolerable climate change. Judging their consequence must, however, always be tempered by the content of Figure 4. Reductions in mitigation cost derived from adaptation could be real if adaptation pushes the boundaries of binding constraints and expands the window of tolerable change. If, on the other hand, adaptation loosens constraints that are not binding in the definition of that window, then adaptation portends an increase in the opportunity cost of continuing to impose more restrictive constraints that are not as pliable.

3. The Limits of Tolerance - Definition and Design Matter

Alternative definitions of tolerable climate change can certainly change the cost of meeting any window target; that goes almost without saying. It is perhaps surprising, though, that definitions of tolerance that are *roughly equivalent* according to (e.g.) economic criteria but different in terms of the adaptation that they envision hold the potential to make *an enormous difference* in setting the window's dimension. This section illustrates this point with one simple example.

Consider, for the sake of the illustration, definitions of tolerable sea level rise. As reported in Section I, more recent discussions of the TWA have offered sea level rise and its decadal pace as a second pair of dimensions for which tolerable change could be defined. Recall that an early ICLIPS analysis [Toth, et al. (1998)] set 30 cm and 3 cm per decade as "conservative" limits of tolerance. These limits were chosen in part to reflect subjective judgments of the pace with which ecosystems can respond to rising seas and in part to reflect the economic vulnerability of developed and undeveloped coastal dryland. In terms of economic vulnerability, Yohe (1990) estimated that the inner-quartile range at the 30 cm limit would put between $44 billion and $92 billion (1990$) of developed property along the coastline of the United States in danger of inundation. For the United States, then, such a limit of tolerable sea level rise would conservatively limit economic vulnerability of developed coastline to less than $44 billion. If the limit were equivalently expressed in terms of the sum property losses *and* protection costs, then were limited to no more than $44 billion), however, then a $44 billion limit could set the sea level rise limit at more than 90 cm [see Yohe and Schlesinger (1998)]. The later estimates are based on opportunity cost estimated with historically-based property value appreciation over time and efficient decisions to protect or abandon built into an adaptive response to rising seas over time.

Table I

Equivalent Estimates for Vulnerability and Cost Limitations for Sea Level Rise in the United States

Assuming No Foresight in Market-based Adaptation[a]

Vulnerability Limits[b]		Equivalent Cost Limits[c]		
Sea Level Rise	Economic Vulnerability	Sea Level Rise	Year	SLR(2100)
20 cm	$30B	90 cm	2100	90 cm
10 cm	$20B	74 cm	2080	90 cm
		73 cm	2090	80 cm
5 cm	$10B	51 cm	2052	90 cm
		50 cm	2059	80 cm
		49 cm	2078	60 cm
		47 cm	2093	50 cm
		43 cm	2105	40 cm

Assuming Perfect Foresight in Market-based Adaptation[d]

Vulnerability Limits		Equivalent Cost Limits		
Sea Level Rise	Economic Vulnerability	Sea Level Rise	Year	SLR(2100)
5 cm	$10B	58 cm	2063	90 cm
		57 cm	2068	80 cm
		55 cm	2090	60 cm
		52 cm	2103	50 cm

Notes:

[a] The no-foresight case assumes that there is no advanced warning to a decision to abandon developed property either because sea level rise has not been monitored or (as is much more likely) individuals and markets did not believe that a decision to abandon would actually be allowed.

[b] Vulnerability reflects the cumulative, undiscounted value (in 1990) of developed property in the United States that would be threatened with inundation by the specified amount of sea level rise; denominated in 1990$.

[c] The columns record, respectively, the amount of sea level rise required to provoke the cumulative, undiscounted costs of abandonment or protection (on a 500m by 500m cell basis) equal to the specified vulnerability estimate in the indicated year along a trajectory that reached the designed height in the year 2100; cost is denominated in 1990$.

[d] The perfect foresight case assumes sufficient time for markets to depreciation threatened structures that will be abandoned to zero.

Sources: Yohe (1990) and Yohe, et al (1996)

Table I explores this vulnerability-opportunity cost equivalence more fully. Equivalent sea level limits are recorded there for each sea level limit proposed to limit vulnerability. The opportunity-cost equivalents are also characterized by the year in which each sea level limit would be binding along alternative sea level rise trajectories (indexed by total increase through the year 2100). Table I shows, for example, that a $10 billion (1990$) limit along a trajectory along which sea level rise would amount to 50 cm by 2100 would, for example, mean that 47 cm of sea level rise through 2093 would be tolerable with no foresight, and so on. Cost equivalent states are, of course, scenario dependent because adaptive responses are themselves scenario dependent; slower trajectories would correspond to 5 cm limit of tolerance along any sea level rise trajectory if only vulnerability were considered. If the $10 billion were a practical limit to the sum of either protection expenditure or the value of abandoned property, then 51 cm

Table II
Representative Emissions Profiles[a]

Case	Population Growth	Technological Change[b]	Depletion[c]	Elasticity of Substitution[d]
1	low	median	high	high
3	median	median	median	high
4	median	median	median	median
5	high	high	high	low

Case	Emissions in 2100	Concentration in 2100	Maximums through 2100	
			Temperature	Rate of Change
1	7.2	547	17.4	0.20
3	20.3	773	18.8	0.37
4	22.1	801	19/0	0.39
5	34.6	1137	19.9	0.48

Notes:

[a] Emissions are measured in billions of metric tons of carbon; concentrations are measured in ppm volume; and temperature is measured in degrees C.

[b] This parameter reflects the rate of technological change in the supply of energy in terms of a secular trend in its real price; high values, for example, signify that, other things being equal, energy consumption would be higher than otherwise because the real price of energy would be relatively lower.

[c] This parameter reflects the degree to which the depletion of fossil fuel resources is reflected in the price of fossil fuel; a high value, for example, suggests that the real price of fossil fuel climbs relatively more rapidly over time as the resource base is depleted.

[d] The elasticity of substitution reflects the ease with which the mix of fossil and non-fossil fuel can be altered in response to changes in the relative prices of energy; a low value, for example, signifies that substitution is difficult and so the fuel mix moves toward non-fossil fuel at a relative more leisurely pace as the relative price of fossil fuel climbs.

of sea level rise could be tolerated through the year 2052 with no foresight along a linear trajectory that would reach 90 cm by the year 2100. Meanwhile, 58 cm could be tolerated through the year 2063 with perfect foresight and associated perfect market adaptation. Along a 50, in particular, give property more time to appreciate, and so a lower sea level limit actually binds further into the future. "Who knows what?" and "When?" are critical questions for researchers who model future adaptation under conditions of uncertainty; and those questions cannot be answered independently of the how the future is envisioned to unfold. Notice, too, that the tolerable limit on sea level rise defined in terms of cost calculations that recognize adaptive potential can be more than ten-times larger than the currency equivalent vulnerability-based limit. As promised, it is clear in one example at least that *defining tolerance so that it accommodates adaptation can make an enormous difference*. But not always. Figures 2 and 4 show clearly that releasing one of the underlying constraints of a window of tolerance may or may not widen the window. The actual effect depends upon whether or not the underlying constraint whose grip has been weakened actually supports much of the window's boundary *in a "policy relevant" region.*

4. Policy Relevance, Adaptation and the Cost of Mitigation in the TWA

The cost of achieving any tolerable window depends critically upon the baseline of unregulated emissions against which mitigation policy must be applied. The results reported here will explore this correlation using 4 representative trajectories that were drawn from the probabilistically weighted futures reported in Yohe and Wallace (1996). They are described briefly in Table II. The Connecticut/Yohe model employed by Wallace and Yohe was designed to produce wide ranges of emissions futures. The model explicitly accommodates Monte Carlo simulation over multiple sources of uncertainty: rates of neutral productivity and populationgrowth, the elasticity of substitution between fossil and non-fossil fuel (in an aggregate production function), the elasticity of substitution between energy and other factors of production, the depletion of fossil-fuel reserves and its manifestation in the real price of fossil fuel, technological change in the supply of energy and the (positive or negative) bias toward non-fossil fuels in that technological development. A procedure described in Yohe (1996) was employed to select interesting and representative emissions trajectories whose underlying specifications could be clearly identified and whose subjective likelihood could be judged from the simulation results.

The existence of time series of cost minimizing and tolerable combinations of temperature and rate of temperature of the sort portrayed in Figure 3 are remarkably robust. Figure 5, though, offers two representations for the median emissions trajectory from Yohe and Wallace [Case (3) in Table II]. The first,

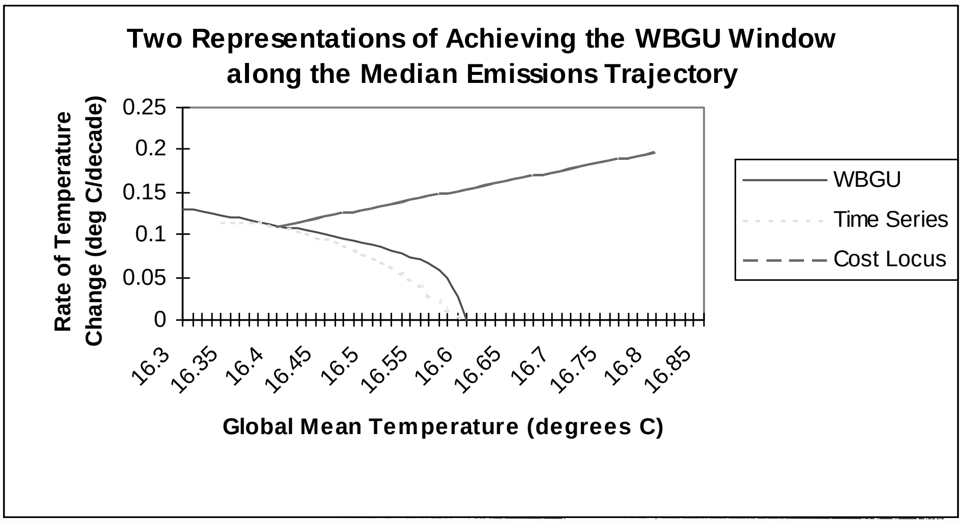

Figure 5. Alternative representations of satisfying the constraints of a tolerable window.

labeled "Time Series" is in fact a time series comparable to the one drawn in Figure 3. It plots ordered pairs of temperature and the rate of temperature change that would emerge from minimizing the discounted cost of abiding by the WBGU window. It enters from the left, intersects the boundary of the window first at (16.4°C , 0.115 °C) in approximately 30 years and then falls to a steady state at (16.6 °C , 0.0 °C). The second, labeled "Cost Locus", highlights combinations of temperature and rate of temperature change that could be achieved by applying cost minimizing mitigation against the underlying emissions trajectory. It, too, intersects the boundary of the window at (16.4 °C, 0.115 °C) indicating the initial point at which the boundary is binding. The representations are equivalent, therefore; and the second turns out to be more convenient for present purposes.

Figure 6 displays four such loci for the four representative emissions trajectories highlighted in Table II. They are all nearly linear in the neighborhood of the WBGU window (a truncated version of which is depicted in Figure 6). As a result, they support the convenient representation of minimum discounted mitigating costs (that actually depend on temperature and the rate of temperature change) as a function of the maximum tolerable temperature, alone. Figure 7 displays those functions for each of the four trajectories. Each is downward sloping; and higher unregulated emissions always portend higher mitigation cost.

Diagnosing the content of Figures 6 and 7 can best be accomplished with reference to the underlying specifications and characteristics of the unregulated emissions trajectories that are recorded in Table II. The first set of four columns highlights the combinations of four critical parameters that define the alternatives.

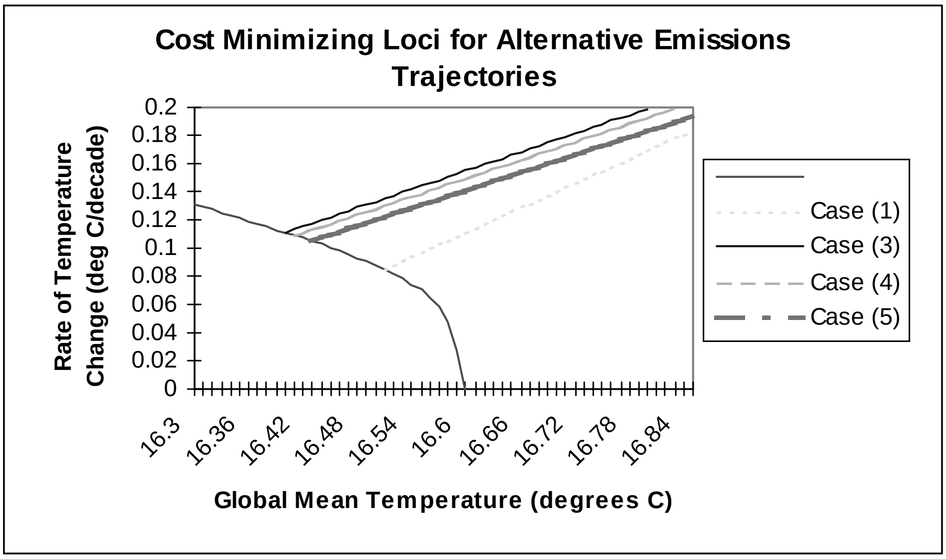

Figure 6. Cost minimizing loci for four alternative emissions scenarios.

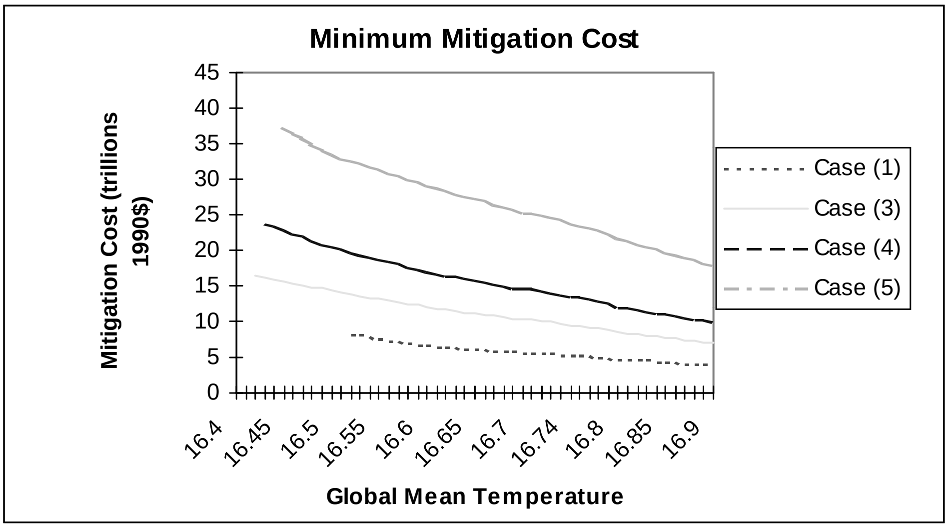

Figure 7. Minimum mitigation cost loci for alternative emissions scenarios.

The second set of columns provide some context by recording emissions, concentrations, and temperature in the year 2100 along unregulated paths as well as the maximum decadal rate of temperature change through 2100. The low emissions path, case (1), corresponds to the lowest cost-minimizing locus in Figure 6 and the lowest cost schedule in Figure 7; but Figure 6 shows that it also commands the lowest maximum rate of temperature increase (and highest maximum temperature) associated with achieving the WBGU window.

Coping with the median emissions trajectory, case (3), is the next least expensive alternative, but it has the highest maximum rate of increase (and lowest maximum temperature) target. Moving from case (1) to case (3) would involve higher population growth and a fossil fuel that is less responsive to resource depletion; and both would serve to make achieving the WBGU window more difficult and more expensive to achieve. Note, though, that difficulty and expense that would both be diminished somewhat by adjusting the specific targeted temperature-rate pair along the tolerable window. Movement to case (4) by lowering the potential for substitution between energy sources would make the task more difficult, still; costs would increase and the target point moves down the window and to the right (lowering the maximum rate constraint but increasing the maximum tolerable temperature). Finally, moving to the highest unregulated emissions path (by increasing population growth even more, reducing substitution potentials even further, and reducing the real price of energy) would exacerbate the cost of achieving the target (at maximum rate and temperature targets that would be still lower and higher, respectively).

Figures 6 and 7 therefore reveal, as expected, that the cost of meeting the target window climbs with unregulated emissions. The relationship between emissions and the targeted combination of maximum temperature and the maximum rate of temperature change is not, however, similarly monotonic. The potential role of adaptation in reducing the (mitigation) cost of sustaining tolerable climate change is, in other words, contingent upon not only the specifics of adaptive potential, but also the underlying drivers of that change. As a result, it is conceivable that these sorts of contingencies could inform the urgency if not the direction of research into adaptive opportunities. Seeing the future unfold with higher than expected population growth could, for example, portent higher mitigation costs and inflate the value of adaptation in the TWA (or the guardrail approach, more generally). Small depletion effects on the price of fossil fuel and/or diminished substitution potential (that might be the result of small depletion effects if the requisite technological innovation is price driven) would do the same. Either would thereby highlight an opportunity for an efficient response (artificially driving the price of fossil fuel up via taxes or encouraging substitution options by market or non-market incentives) that could be balanced against an evolving understanding of adaptive strategies.

Figures 8a and 8b display the potential for this "balancing act" by displaying, as rays drawn from the WBGU window, portions of the cost minimizing loci associated with reducing mitigation costs by 10% and $2 trillion (1990$ in discounted value). The relative lengths of the rays are thus indicative of the

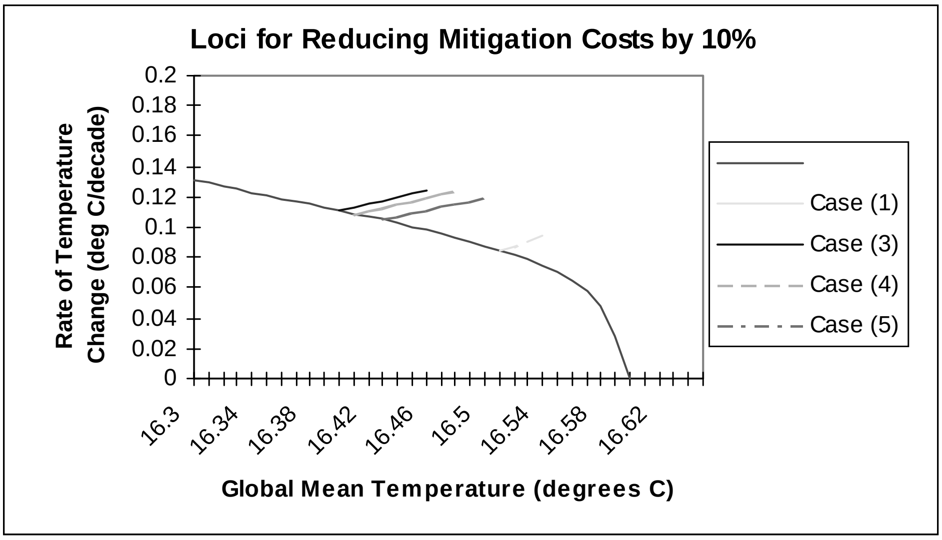

Figure 8a. Cost minimizing loci for 10% reductions in mitigation costs.

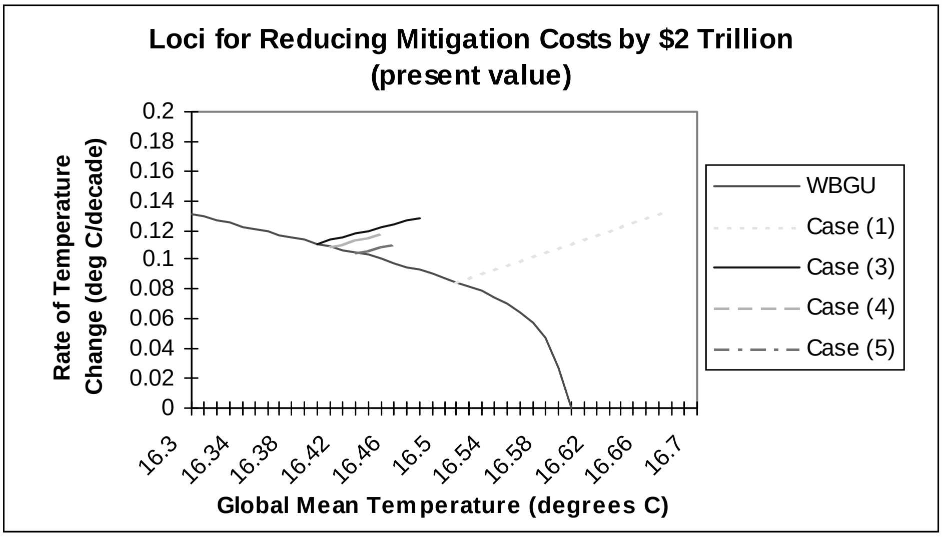

Figure 8b. Cost minimizing loci for reducing mitigation costs by $2 trillion (1990$) in present value.

adaptive effort required to achieve the designed cost savings. As might be expected, the lengths of the 10% rays grow with emissions. The $2 trillion cost reduction rays are, however, more germane in quantifying prospective economic benefit of improved adaptation, and their lengths are inversely related to emissions. It is, quite simply, easier to lower the $38 trillion cost of achieving the WBGU window along a high emissions trajectory like case (5) by $2 trillion than it is to lower the $7.5 trillion initial cost along a low emissions trajectory like case (1).

5. Tradeoffs when Maximum Rate and Levels are Correlated in the Window

The complexity of multiple targets for alternative emissions trajectories is clearly depicted in Figures 8a and 8b; but they are a bit misleading because they show only half of the story. They depict, in particular, loci of cost minimizing combinations of specific policy targets that would be chosen if the tolerable window were to be enlarged by adaptive potential and/or better understanding of the underlying processes that define "tolerance". They miss, however, the observation that any point along any ray could be supported by a multiplicity of new windows defined by a comparable number of combinations of larger temperature and rate of temperature boundaries. Refer to Figure 9 to see how. For purposes of illustration, an exaggerated cost minimizing locus for the median emissions trajectory is drawn there emanating from the original WBGU window;

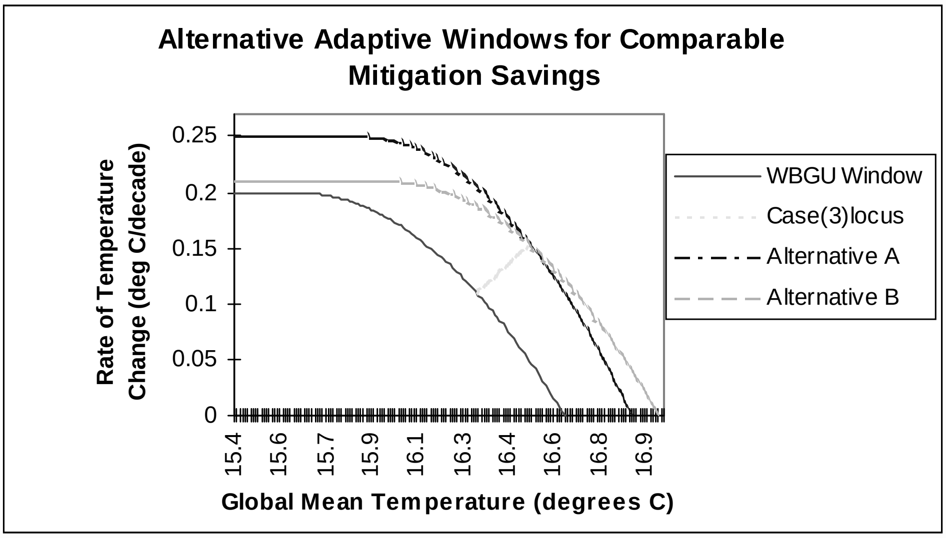

Figure 9. Alternative tolerable windows for comparable mitigation savings.

indeed, moving to its upper endpoint would reduce the present value of the cost of achieving less restrictive tolerable climate change by nearly $5 trillion (1990$). Two alternative tolerable windows that would sustain these cost savings are also drawn assuming the quadratic negative correlation employed by Toth, et al. (1998) in their seminal exploration. The first relaxes the absolute maximum rate of change constraint by 0.01°C per decade, but it requires a corresponding increase in the maximum temperature of 0.345°C; the second contemplates an increase of 0.05°C per decade in the rate constraint, but only a 0.25°C increase in the absolute temperature limit.

Figure 10 brings this observation to bear on alternative combinations of relaxed rate and temperature limits that would reduce the mitigation cost of achieving a specified window by 10%. There are, for each alternative emissions trajectory, an infinite number of combinations that would work. For the median trajectory, for example, increasing the maximum allowed temperature alone by almost one degree would do the trick. So would relaxing increasing the rate of change limit by 0.123°C to something like 0.323°C per decade; and so would any combination along the convex locus drawn connecting these two limits. As usual, the point is not necessarily to believe the numbers, exactly. It is, instead, to recognize that exploring adaptive potential along all dimensions can pay off. Loci of the sort drawn in Figure 10 reflect both the potential payoff of such exploration *and* the tradeoffs that should be exploited when the relevant boundary reflects an underlying correlation.

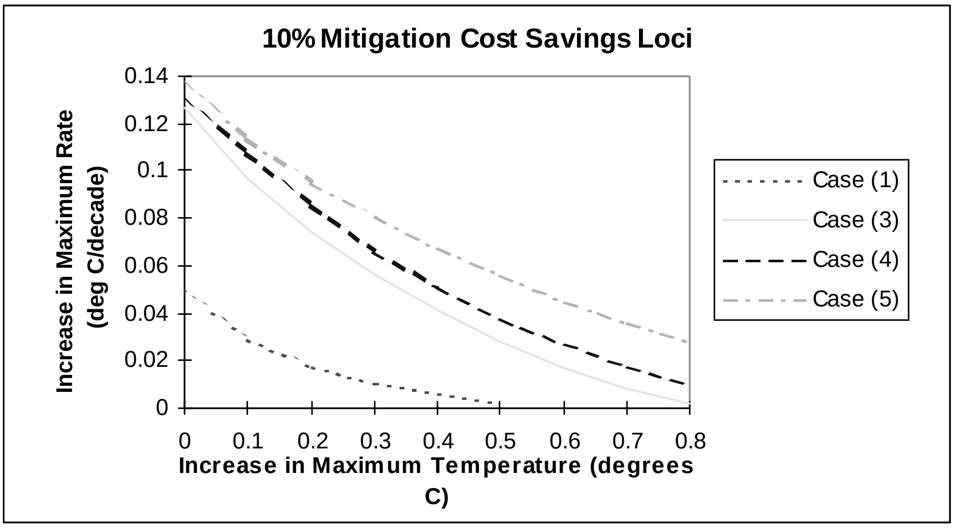

Figure 10. Loci of 10% cost savings for alternative emissions scenarios.

Figure 10 offers some preliminary insight into the critical tradeoffs at least for temperature change. The savings loci are higher and flatter (and thus harder to achieve) for higher emissions trajectories. There is, in fact, an apparent limit to the value of relaxing absolute limit in the rate of change dimension. To understand why, recall that the cost minimizing point moves down and to the right along any window anticipated emissions climb, at least as soon as higher emissions are driven by something other than higher rates of population growth. The potential value of a higher rate of change limitation is thus undercut significantly by the economics of achieving tolerable change when unregulated emissions are higher than might be expected along the median trajectory. Correspondingly, higher emissions profiles amplify the potential value of a higher temperature limit. Quite simply, then, insight into the likely trajectory of emissions of harmful gases can greatly inform decisions about where to target research into adaptive possibilities.

6. Lessons and Context

This paper reports the results of an initial attempt to bring adaptation to bear on the emerging "guardrail" approach to evaluating climate change policy. The guardrail approach is designed to separate explicitly the analytical issues involved in improving our understanding of the science of climate change and climate change policy from the normative issues involved in framing our response to that understanding. This work focuses specifically on the multi-dimensional "tolerable windows" approach that has been adopted by the Scientific Advisory Council on Global Change to the Federal Government of Germany (the WBGU) and incorporated into the ICLIPS Project of the Potsdam Institute for Climate Impact Research (PIK). It is neither systematic nor comprehensive in its coverage; but it does offer some insights that are likely to be both robust and economically significant.

First of all, the underlying metric with which the physical limits of tolerable climate change are defined can make an enormous difference. Section 3 illustrates this point in terms of sea level rise. Limiting sea level rise in terms the vulnerability of developed property losses along the United States coastline can set the physical boundary of tolerable change as much as 90% lower than comparable physical limits defined in terms of nominally equivalent sums of protection expenditures and abandonment costs. The key is that estimates of vulnerability preclude adaptive responses to rising seas while economic cost calculations embrace them. Section 4 moves beyond the sea level context to note that increasing adaptive potential along one dimension of climate change (e.g., the level of temperature change) can increase flexibility in choosing least-cost means of coping with change along many other dimensions (e.g., the rate of temperature change) when the multi-dimensional boundaries of tolerance are correlated. Higher tolerance of higher temperatures can, for example, allow a least cost climate policy to target a higher limit on the rate of temperature change and still stay within a predetermined level/rate window of tolerance. Section 4 shows that this sort of increased flexibility can reduce the cost of staying within the tolerable boundaries by trillions of constant dollars (in present value) - amounts that can be expressed as significant fractions of gross world product both today and in the future. Section 5 meanwhile demonstrates that size of these potential savings is highly correlated with anticipated emissions trajectories of the offending greenhouse gases. Low emissions futures correspond, more specifically, to higher temperature and lower rate constraints over the medium term that are relatively less expensive to achieve. Adaptation that alters the definition of tolerable change will, in such cases, reduce the cost of compliance by less than comparable adaptation along higher (but nonetheless "median" best guess) emissions trajectories where lower temperature and higher rate targets apply. High emissions trajectories offer the largest opportunities for cost savings, but compliance is then most expensive.

It must finally be emphasized once again that adaptation does not just happen in the most efficient way, in part because its exploration is not centralized, but also in part because emissions trajectories and thus cost-minimizing targets are uncertain. As a result, the value of improved adaptation along any dimension of tolerable change is highly dependent upon *the path of future emissions, their associated climate impacts, and their timely recognition.* It must also be emphasized that tolerable change will, over the long term, be measured in multiple dimensions and that the ultimate window of tolerance can be viewed as the intersection of multiple constraints projected onto a common metric-space (like the level and rate of temperature change). As a result, improved adaptation in one dimension of an underlying constraint, even if it allows improved flexibility along the boundary of that constraint may be essentially worthless if other constraints defined in other units continue to bind. Care should therefore be taken in designing not only mitigation strategies, but also in directing research into areas where improved adaptive potential can actually make a difference by allowing flexibility along a functioning constraint. Improved potential for adaptation by human systems may have not any effect on mitigation costs if they simply move boundaries of tolerable climate change that are not binding. In such cases, potential reductions in cost are not realized, and so they represent increases in the opportunity cost of holding fast to the constraints that are, in fact, binding.

Perhaps the most important distinction to be made in this regard is that adaptation can be expected to play a large role in defining windows of tolerable climate change derived from the response functions of managed impact sectors. By way of contrast, we have little way of judging the ability of unmanaged systems (like natural ecosystems) to adapt and even less of an idea about how to improve that ability. Indeed, it may be very difficult for these systems to adapt even with heroic anthropogenic assistance (migration corridor maintenance, landscape engineering, etc.). If this is the case, then improvement in the ability of human systems to cope with climate change and climate variability will only serve to increase the opportunity cost of restricting climate change to the more restrictive and more rigid limits of unmanaged natural systems. Expressed more optimistically, better human adaptation will increase the value of information about how similar improvement might be brought to bear on the ecological side of the ledger.

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