Did the Stern Review underestimate US and global climate damages?

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ABSTRACT

The Stern Review received widespread attention for its innovative approach to the economics of climate change when it appeared in 2006, and generated controversies that have continued to this day. One key controversy concerns the magnitude of the expected impacts of climate change. Stern's estimates, based on results from the PAGE2002 model, sounded substantially greater than those produced by many other models, leading several critics to suggest that Stern had inflated his damage figures.

We reached the opposite conclusion in a recent application of PAGE2002 in a study of the costs to the US economy of inaction on climate change. This article describes our revisions to the PAGE estimates, and explains our conclusion that the model runs used in the Stern Review may well underestimate US and global damages. Stern's estimates from PAGE2002 implied that mean business-as-usual damages in 2100 would represent just 0.4 percent of GDP for the United States and 2.2 percent of GDP for the world. Our revisions and reinterpretation of the PAGE model imply that climate damages in 2100 could reach 2.6 percent of GDP for the United States and 10.8 percent for the world.

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1. Introduction

The Stern Review received widespread attention for its innovative approach to the economics of climate change when it appeared in 2006. It represented a break with conventional analyses in several respects, generating debates about climate economics that have continued to this day. One of the foundations of the Stern analysis was the use of the PAGE2002 model (Alberth and Hope, 2007; Hope, 2006; Wahba and Hope, 2006) to estimate the damages that would be expected under business-as-usual conditions (i.e., in the absence of effective new climate policies). Based on PAGE, Stern estimated that the present welfare cost of climate damages through 2200 could amount to 5 percent of world output under a relatively narrow definition of damages, up to as much as 20 percent under the broadest definition. These estimates were substantially greater than those produced by many other models, leading several critics to suggest that Stern had inflated his damage figures (Byatt et al., 2006; Lomborg, 2006; Mendelsohn, 2006; Nordhaus, 2007; Tol and Yohe, 2006).[1]

We reached the opposite conclusion in a recent application of the PAGE2002 model. In a study of the costs to the US economy of inaction on climate change, we had initially planned to use the US estimates from Stern's PAGE runs. These estimates, however, turned out to be surprisingly small, and seemingly inconsistent with other, bottom-up calculations of climate damages in the United States. Our recent study of the costs to the US economy of inaction on climate change takes a different approach, building up damage estimates for specific sectors where data and analyses are available (Ackerman and Stanton, 2008). That study projects annual damages equal to 1.8 percent of US GDP by 2100 from just four economic sectors: hurricane damages, residential real estate losses due to sea-level rise, energy sector costs, and water supply costs.

This article describes our revisions to the PAGE estimates for the United States, and explains our conclusion that the model runs used in the Stern Review may well underestimate US and global damages. (Note that we are using PAGE and PAGE2002 interchangeably; there are no references to other versions of PAGE in this article.) Section 2 describes the PAGE model. Section 3 presents the model results used in the Stern Review—including disaggregation by region, a feature that was not highlighted by Stern. Sections 4 through 6 explain three principal reasons why the results may be too low for some or all regions:

- extensive and nearly costless adaptation was assumed to occur, especially in high-income countries;
- the risk of discontinuous, catastrophic losses was treated more timidly in the model than in the text of the Stern Review; and
- the overall shape of the (non-catastrophic) damage function was based on very conservative guesses.

Section 7 introduces the problem of uncertainty and worst-case risks, as raised in recent work by Martin Weitzman, and

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  [1] For a summary of these critiques, see Ackerman (2008).

suggests a partial response to this problem, leading to a further increase in the damage estimates that are relevant for policy purposes. Section 8 briefly concludes.

2. The PAGE2002 model

PAGE2002 is a simulation model, estimating the climate consequences and damage costs that result from a user-specified emissions scenario. It uses a number of simplified formulas to represent the complex scientific and economic interactions of climate change. A full description of the model can be found in Hope (2006). Most of the model's coefficients and data ranges are calibrated to match the projections of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001). Projections of GDP, population and emissions of greenhouse gases are taken from the 2001 version of IPCC Scenario A2.[2] Because many aspects of climate change are subject to uncertainty, PAGE uses probability distributions, based on the best available estimates found in the literature, to represent 31 key inputs to the calculations. Using these input distributions, PAGE performs a Monte Carlo analysis; the most frequently reported results from PAGE are the mean outcomes from 5000 runs of the model. (Alternative approaches to uncertainty are discussed in Section 7.)

The model includes ten time intervals spanning 200 years, divides the world into eight regions, and explicitly considers three different greenhouse gases (carbon dioxide, methane, and sulphur hexafluoride) with other gases included as an excess forcing projection. Three types of impact are calculated:

- economic impacts, which are impacts on marketed output and income, in sectors such as agriculture and energy use, that are directly included in GDP;
- non-economic impacts, which are impacts on things like health and wilderness areas which are not directly included in GDP; and
- discontinuity impacts, which are the increased risks of climate catastrophes, such as the melting of the Greenland or West Antarctic ice sheet.

These three types of impacts are summed to calculate total impacts.

The Stern Review team modified a small number of inputs for their use of the model (Stern, 2006). The version used in the Stern report differed by using purchasing power parity exchange rates throughout, a change which increases the weight of developing countries in the global totals. The Stern version also calculated the discount rates for each time period and region, using a Ramsey-type optimal growth function (Cline, 2004). In Stern's notation, the discount rate r is the sum of pure time preference ρ, plus the product of the elasticity of marginal utility of consumption η and the growth rate of per capita consumption g for each region i and time period t:

$$r_{i,t} = \rho + \eta g_{i,t} \tag{1}$$

In this equation, Stern set $\rho = 0.1$ percent per year and $\eta = 1$. The growth rate, and therefore the discount rate, varied with different runs of the Monte Carlo analysis; the average value of the discount rate was 1.4 percent per year, well below the discount rates used in many other analyses (although not unprecedented;

see Cline (2004), and Ackerman and Finlayson (2006) for climate analyses with similar discount rates).

Previous applications of PAGE2002 typically treated pure time preference as a Monte Carlo variable, using a range of $\langle 1, 2, 3 \rangle$ for ρ (here, and throughout this article, the triangular brackets denote a triangular probability distribution with $\langle$ minimum, most likely, maximum $\rangle$ parameter values). Stern's lower rate of pure time preference led to lower discount rates, and hence to higher present values for future damages. As a result, the Stern Review gave a mean estimate of the social cost of carbon (SCC) of $85 per tonne of CO_2, or $312 per tonne of carbon (Stern, 2006), much higher than most previous estimates using PAGE2002, which have been in the range of $20 to $65 per tonne of carbon (Hope, 2005, 2006).

In addition to the basic estimates, calibrated to the IPCC's 2001 scenarios, the Stern team developed a high climate sensitivity scenario. This incorporated a number of technical changes based on research since 2001, reflecting the risk that increasing concentrations of greenhouse gases may be changing the climate more rapidly than was previously believed. Stern's high climate sensitivity estimates generally showed damages about 40 percent greater than the comparable basic estimates. For simplicity, we will focus only on the basic estimates in this article.

3. Stern's US and global results from PAGE2002

The widely reported damage estimates from the Stern Review were expressed in terms of "balanced growth equivalents"—that is, the uniform reduction in growth throughout the two-century forecast period (to 2200) that would have the same present value as the estimated pattern of damages. This is a logical and informative measure, but it is relatively unfamiliar and cannot be directly compared to other models. For the sake of familiarity and comparability with other estimates, we will instead describe scenario results in terms of the annual damages in the year 2100, as a percentage of that year's GDP. Damages in 2100 will be generally lower than Stern's 200-year balanced growth equivalent, since PAGE estimates that damages will increase markedly after 2100. By comparing a future year's damages to the same year's GDP, we can avoid the difficult questions of discounting: regardless of discount rate, both numerator and denominator would be discounted by the same factor, so the ratio of damages to GDP would be unchanged.

The basic Stern Review damage estimates for 2100 are shown in Table 1. All figures are the mean results from a Monte Carlo analysis with 5000 runs, expressed as a percentage of world or regional GDP in 2100.

As Table 1 shows, Stern's estimates of damages at the end of the century were heavily concentrated in the developing countries. Total world damages, the indicator that gets the most attention, suggests noticeable losses. However, as late as 2100, projected economic damages in high-income countries, along

Table 1
Mean business-as-usual damages in 2100—Stern Review version.

	Annual damages as percent of GDP in 2100			
	Economic	Non-economic	Catastrophic	Total
USA	–	0.3	0.1	0.4
Other OECD	–	0.8	0.2	1.0
Rest of world	0.8	1.7	0.4	3.0
World total	0.6	1.4	0.3	2.2

Source: 5000 runs of the PAGE2002 model.
Note: '–' denotes less than 0.05%.

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[2] A2 is the IPCC scenario with the second highest emissions. At the 83rd percentile it predicts a global average temperature increase of 5.4 °C in 2100. Its mean prediction is 3.4 °C in 2100.

with catastrophic damages everywhere, remain surprisingly close to zero. These results seem anomalous in the Stern Review—a report that described itself, and was widely taken by others, as a warning of the severity of impending climate damages.

If the results in Table 1 are accepted as reasonable forecasts, then the costs of a business-as-usual climate scenario are concentrated in near-term impacts on developing countries, in worsening worldwide conditions after 2100 (since Stern's calculations ran through 2200, and the low discount rate gave significant weight to the later damages), and to a lesser extent in the non-economic, non-catastrophic damages in high-income countries. This is a possible but unsatisfying explanation: it appears inconsistent with the growing evidence that climate impacts are already being felt in the global North (used here as shorthand for high-income or OECD countries); and it could be read, in cynical terms, to support a parochial complacency in those countries. If serious impacts on the North are more than a century away, the narrowly self-interested Northern citizen might wonder, isn't this really someone else's problem?

Alternatively, it is possible that the Stern estimates understate the near-term economic impacts on the global North, and the risk of catastrophic change everywhere. A closer look at PAGE2002 and its parameters, in the next three sections, supports this alternative interpretation.

4. Adaptation assumptions

The PAGE2002 defaults, adopted by the Stern Review, assume that substantial, nearly costless adaptation will occur; the reported damage estimates are for damages remaining after that adaptation takes place. Specifically, PAGE assumes that in developing countries, 50 percent of economic damages are eliminated by low-cost adaptation. In OECD countries, the assumption is even stronger: 100 percent of the economic damages resulting from the first 2 degrees of warming, and 90 percent of economic damages above 2 degrees, are eliminated. For non-economic, non-catastrophic damages, adaptation is assumed to remove 25 percent of the impact everywhere. (No adaptation is assumed for catastrophic damages, which are discussed in Section 5.)

The adaptation assumptions sharply reduce reported damages everywhere, but have a much greater impact on OECD countries. It is hard to evaluate these assumptions: there undoubtedly will be some adaptation, particularly to the early stages of warming, and it seems plausible that richer countries will often be more successful in adaptation. Yet the experience of the European heat wave in 2003 and the impacts of Hurricane Katrina in the United States in 2005 might cast doubt on the assumption of 90–100 percent adaptation. Even in the richest countries, which have ample physical and economic resources for adaptation to many early impacts of climate change, there can be failures of planning, political will, and implementation.

It seems more informative and transparent to report the model results for gross damages, under a "no adaptation" scenario. The PAGE results, comparable to Table 1 above but with no assumed adaptation, are shown in Table 2. The totals are larger, and economic damages in OECD countries have become relatively larger in comparison to other categories. Only the catastrophic damages remain unchanged.

Modeling the no-adaptation scenario is not meant to imply that this is a likely outcome; there will undoubtedly be successful adaptation to many aspects of climate damages. It is useful as a starting point, however, to see how much potential damage needs to be addressed by either adaptation or mitigation. That damage estimate can then be compared to the costs of adaptation and mitigation. In contrast, Stern's quantitative results are only

Table 2
Mean business-as-usual damages in 2100, "no adaptation" scenario.

	Annual damages as percent of GDP in 2100			
	Economic	Non-economic	Catastrophic	Total
USA	0.3	0.4	0.1	0.8
Other OECD	0.7	1.0	0.2	1.9
Rest of world	1.6	2.3	0.4	4.3
World total	1.2	1.8	0.3	3.4

Source: 5000 runs of the PAGE2002 model.

presented as the net effect after an assumed but unspecified high level of low-cost adaptation—a presentation that obscures the extensive need for adaptation expenditure.

Damage estimates for the no-adaptation scenario, in Table 2, remain smaller for the US than for other OECD countries; this results from a separate, intentional assumption. Compared to other rich countries, the US has proportionally much more of its population, economic activity, and capital stock in the interior of the country, rather than on the coast. Since sea-level rise and storm surges are among the most important early impacts of climate change, it is reasonable to adopt lower damage estimates for the US than for Europe, Japan, and other high-income countries.

5. Thresholds and probabilities for climate catastrophes

PAGE assumes that a threshold temperature (measured in degrees above a recent base year) must be reached before catastrophic events become possible; once that threshold is crossed, the probability of catastrophe gradually rises along with the temperature. Two of the uncertain (Monte Carlo) parameters in PAGE are involved here. One is the threshold temperature, with minimum, most likely, and maximum values of $\langle 2, 5, 8 \rangle$ degrees Celsius in the Stern analysis. Much of the discussion of potential catastrophes, such as the loss of the Greenland or West Antarctic ice sheets, has suggested that they become possible or even likely at temperatures well below the PAGE model's "most likely" threshold of 5 °C of warming; indeed, the narrative portions of the Stern Review make this suggestion. For this reason, the PAGE baseline assumption about threshold temperatures seems too conservative. We changed the threshold temperature to minimum, most likely, and maximum values of $\langle 2, 3, 4 \rangle$ degrees Celsius. Even this may still be conservative, in light of recent research suggesting non-zero probability of catastrophic outcomes at 2 °C warming (Baer and Mastrandrea, 2006; Meinshausen, 2006).

A second parameter involved in this calculation is the rate at which the probability of catastrophe grows, as the temperature rises past the threshold. In the PAGE defaults, used by Stern, the probability of catastrophe increases by minimum, most likely, and maximum rates of $\langle 1, 10, 20 \rangle$ percentage points per degree Celsius above the threshold. This also seems unduly conservative, minimizing the risk of catastrophe until warming is far advanced. In our changes to the model, the probability of catastrophe grows at minimum, most likely, and maximum rates of $\langle 10, 20, 30 \rangle$ percentage points per degree Celsius above the threshold.

6. The shape of the damage function

PAGE, like many economic models, assumes economic and non-economic climate damages are a function of temperature,

using a simple equation of the form

$$\text{Damages} = aT^N \tag{2}$$

Here, a is a constant, T is the temperature increase, and N is the exponent governing how fast damages rise. If $N = 2$, then $4°$ is four times as bad as $2°$; if $N = 3$, then $4°$ is eight times as bad, etc.

PAGE treats the exponent N as one of the uncertain parameters that is allowed to vary in the Monte Carlo analysis, with the minimum, most likely, and maximum values, respectively, set at $\langle 1, 1.3, 3 \rangle$. There is essentially no evidence bearing directly on the value of this exponent, but the "most likely" value of 1.3 seems almost timid: it implies that $4°$ is only about 2.5 times as bad as $2°$. In our variation, we set the minimum, most likely, and maximum values of the exponent at $\langle 1.5, 2.25, 3 \rangle$. This alternative keeps the exponent within the same range used in the Stern Review, but weights the higher end of the range more heavily; it assumes that the exponent is most likely to be a little more than 2, the value used in many recent models.

The combination of our changes to the threshold for catastrophic events, and to the damage function exponent, more than doubles the projected damages from the no-adaptation scenario by 2100, as shown in Table 3. Comparing Tables 2 and 3, all categories show an increase in damages; the difference is greatest in the catastrophic risk category.

7. Worst-case versus average damages

Although Stern emphasized and expanded the role of uncertainty in climate economics, another economist has argued that the problem goes even deeper. Martin Weitzman (2009) maintains that in complex, changing systems such as the global climate (or financial markets), we are inevitably forecasting the future based on limited information. As a result, we cannot learn enough to be confident about how bad, and how likely, the worst-case possibilities may be. If, for example, we had to estimate how fast the average temperature will increase based on 100 experimental observations, we could not say much about the 99th percentile – that is, one of the worst cases – of possible outcomes. Yet when faced with real, open-ended risks, people care a great deal about worst-case outcomes, out to the 99th percentile of possibilities and beyond. More formally, Weitzman proves that because the probabilities of key climate parameters are inferred from limited information, the resulting "fat-tailed" probability distributions imply that the expected value of harm – or equivalently, the value of reducing emissions and damages – can, in technical terms, become infinite. The message for climate change, according to Weitzman, is that we should worry less about calibrating the most likely outcomes, and more about insurance against worst-case catastrophes.

IPCC (2007) discusses the important concept of "climate sensitivity", i.e. the expected temperature change from a doubling of atmospheric carbon dioxide; this is of immediate relevance because the world is likely to reach twice the pre-industrial level of carbon dioxide within this century. (If current emission trends do not change, that level could be reached in the first half of the century.) The IPCC's best estimate of climate sensitivity is an increase of $3°C$ as a result of a doubling of atmospheric carbon dioxide—well within the range of the ongoing debate over the impacts of predictable and expected damages. Weitzman argues, however, that the same IPCC reports imply that the 95th percentile value for climate sensitivity is $7°C$, and the 99th percentile value is $10°C$. Feedback mechanisms discussed in the scientific literature suggest that the eventual temperature change could be even greater, perhaps a 95th percentile of $10°C$ and a 99th percentile of $20°C$. Discussing a temperature increase of $10–20°$, he says:

> …such high temperatures have not been seen for hundreds of millions of years

> …Because these hypothetical temperature changes would be geologically instantaneous, they would effectively destroy planet Earth as we know it. At a minimum such temperatures would trigger mass species extinctions and biosphere ecosystem disintegration matching or exceeding the immense planetary die-offs associated in Earth's history with a handful of previous geoenvironmental mega-catastrophes. (Weitzman, 2009, p. 5)

A Monte Carlo analysis, in a model such as PAGE, allows at least a limited measurement of the worst-case risks emphasized by Weitzman. Since PAGE estimates are based on 5000 runs of the model with varying parameters, it is easy to determine the 95th, 99th, or any other percentile outcome.

As a partial step toward the focus on worst-case outcomes, we examined the upper end of what IPCC considers "likely" to occur. In the formal IPCC interpretation of the term, "likely" means a 66 percent probability of occurring, so the likely range of outcomes extends from the 17th to the 83rd percentile. Therefore, we took the 83rd percentile outcome from the PAGE runs as representing the worst of what is likely to occur. Table 4 presents 83rd percentile outcomes, for the same scenario as Table 3—the difference is that Table 3 presents the mean outcomes for the scenario. As Table 4 shows, even this limited movement toward worst-case outcomes has a substantial effect on the estimate of damages. Moving farther toward worst-case results would lead to bigger damages; Table 5 presents the 95th percentile estimates of damages, which are, in many categories, roughly 60 percent greater than the 83rd percentile damages in Table 4.

Table 3
Mean business-as-usual damages in 2100: no adaptation, increased catastrophe risk and increased damage exponent.

	Annual damages as percent of GDP in 2100			
	Economic	Non-economic	Catastrophic	Total
USA	0.4	0.5	0.6	1.5
Other OECD	0.9	1.3	1.6	3.8
Rest of world	2.0	2.9	3.2	8.2
World total	1.6	2.3	2.6	6.4

Source: 5000 runs of the PAGE2002 model.

Table 4
Business-as-usual damages in 2100: 83rd percentile estimates (no adaptation, increased catastrophe risk and increased damage exponent).

	Annual damages as percent of GDP in 2100			
	Economic	Non-economic	Catastrophic	Total
USA	0.6	0.9	1.2	2.6
Other OECD	1.4	2.0	3.1	6.2
Rest of world	3.2	4.5	6.3	13.5
World total	2.5	3.6	4.8	10.8

Source: 5000 runs of the PAGE2002 model.
Note: As the impacts are closely but not perfectly correlated, the 83rd percentile of the total damages is slightly less than the sum of the 83rd percentiles of the damages in the individual impact categories.

Table 5
Business-as-usual damages in 2100: 95th percentile estimates (no adaptation, increased catastrophe risk and increased damage exponent).

	Annual damages as percent of GDP in 2100			
	Economic	Non-economic	Catastrophic	Total
USA	1.1	1.5	2.0	4.3
Other OECD	2.4	3.4	5.0	9.9
Rest of world	5.4	7.9	10.1	21.5
World total	4.2	6.1	8.0	16.8

Source: 5000 runs of the PAGE2002 model.
Note: As the impacts are closely but not perfectly correlated, the 95th percentile of the total column is slightly less than the sum of the 95th percentiles of the individual impact categories.

8. Conclusions

In our estimation, the Stern Review's version of PAGE2002, far from inflating damages, is more likely to have understated the potential costs of climate change for the United States and for the world. This is not only because of the revisions described in this article, but also because our research on US impacts suggests a much larger estimate of damages (Ackerman and Stanton, 2008). The damages estimated in that study, 1.8 percent of US GDP by 2100, represent impacts projected in just four economic sectors under a business-as-usual scenario (the 83rd percentile of the IPCC's A2 scenario), with no significant mitigation of greenhouse gas emissions or adaptation to prevent damages. They do not include any valuation of externalities, or estimates of damages due to catastrophic risks.

These sectoral estimates are all subsets of PAGE's economic category of damages; they are most comparable to the PAGE results under the assumptions used in Table 4. As seen there, PAGE2002 projects annual economic damages from all sectors in the United States by 2100 equal to 0.6 percent of GDP at the 83rd percentile with no adaptation, increased risk of catastrophe and an increased damage function. In short, our disaggregated estimate for four sectors is three times the size of the comparable PAGE2002 estimate for all sectors. Thus the aggregate economic damages modelled in PAGE2002 would seem to represent an underestimate when compared to disaggregated damages projected for the United States on a sector by sector basis.

Because of the similarity in PAGE2002 parameter values chosen for the United States and for other nations, it is likely that the Stern Review results underestimate damages for all industrialized nations. As a consequence, projected total damages worldwide will be a much bigger share of global GDP under our assumptions than in the version reported by Stern. Indeed, the global damage calculation for 2100, combining economic, non-economic, and catastrophic risks, rises from 2.2 percent of GDP in the Stern version of PAGE (our Table 1) to 10.8 percent in our final version (Table 4).

Our revisions have a proportionally greater effect on damages in OECD countries: the estimated total damages in Table 4 are more than 6 times as great as in Table 1 for both the United States and other OECD, compared to 4.5 times as great for the rest of the world. Nonetheless, our modified PAGE2002 results still imply that damages are more than twice as large, relative to GDP, in developing nations as in the OECD: the costs of climate change – economic, non-economic and catastrophic – will be far more severe in the places that have contributed the least to global emissions and that can least afford adaptation measures.

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