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The *Stern Review*: A deconstruction

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ABSTRACT

Using a simple model designed for transparency but nonetheless calibrated to support the much-quoted damage estimates of the *Stern Review of the Economics of Climate Change*, we demonstrate significant sensitivity of those results to assumptions about the pure rate of time preference, the time horizon, and the rates of risk and equity aversion used to compute certainty- and equity-equivalent annuities. Most importantly, we demonstrate enormous sensitivity to presumed constant regional vulnerability and underlying assumptions about adaptive capacity. Manipulation of any of these parameters one at a time across reasonable ranges can diminish damage estimates by as much as 84% or, in the case of extending the time horizon with the *Review's* low discount rate, increase damage estimates by 900%. We also confirm the usual result that limiting atmospheric concentrations to specific benchmarks above 400 ppm cannot eliminate all damages. Nonetheless, we applaud the *Stern Review* author team for reconfirming that the climate problem can be approached productively as an economic problem whose solutions can be explored with the tools of decision analysis.

1. Introduction

The first media reports that circulated prior to the release of the *Stern Review of the Economics of Climate Change* (Stern et al., 2006a) were dismissed quickly as journalistic hyperbole. The *Stern Review* was going to report the results of what was essentially intended to be a literature survey attached to some standard integrated modeling. The numbers quoted in the press were clearly outside the range of conventional wisdom; and so many observers were skeptical that a literature review could have produced such an outlier in its damage estimates. Were they correct, or was it possible that sound economic analysis could support damage estimates that were orders of magnitude higher than conventional wisdom? It turned out that these observers were onto something. Summarizing the literature, the authors of the *Stern Review* had somehow managed to produce estimates of economic damages that were up to 100 times larger than the average of the numbers they had synthesized.

We have, in earlier papers, presented qualitative discussions of how and why the *Stern Review* is an outlier (Tol, 2006; Tol and Yohe, 2007a; Yohe and Tol, 2006; Yohe et al., 2007). Arrow (2007), Baer (2007), Dasgupta (2007), Maddison (2006), Mendelsohn (2006), Nordhaus (2007a, b), Pielke (2007), Varian (2006) and Weitzman (2007) all added their own variations on the same theme. These authors all argue, in one way or another that the *Stern Review* seemed to be "right for the wrong reasons"; that is, an economic case for immediate emission reduction can be made, but the *Stern Review* failed to do so. A number of authors expressed the fear that a case made badly, in a polarized political debate, could backfire.

Yohe (2006) presented a quantitative reconstruction of the *Stern Review*'s headlines—climate change damages of "5–20% of GDP, now and forever"; he found that up to 50% of the damage estimates were captured in the post 2200 residual. Here, we report on the results of a more extensive exercise designed explicitly to explore the roles of a small set of significant parameters and modeling assumptions within a structure that was specifically constructed expressly to maximize transparency even as it was calibrated to track the *Review's* estimates. Hope (2007) uses the PAGE2002 model (which was also used by the authors of *Stern Review*) to the same purpose. The objective of this paper is therefore to present further but more accessible quantitative results on the lack of robustness of one of the main conclusions of the *Stern Review*, namely that the economic impact of climate change is dramatically large.

As in any such analysis, some of the results are not particularly surprising, but they serve to reassure us that our simple model is

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not, itself, an outlier. Other results, particularly those related to the evolution of regional vulnerabilities to climate impacts (net of exercised adaptation potential) across developed and developing countries, add some new insight. The received wisdom is that the *Stern Review* is an outlier because it uses a low discount. We show that this is too simple a view. Other assumptions in the *Stern Review* are important too.

This work focuses on some of the major critiques of the *Review's* estimates of the economic impacts of climate change; they can be summarized in a series of succinct statements:

1. Stern et al. (2006a, b) use an extraordinarily low discount rate without reporting a sensitivity analysis.[1]
2. The time horizon is too short for the chosen discount rate.
3. The low discount rate does not match the equally low assumed rate of risk aversion.[2]
4. Stern et al. (2006a, b) do not separate risk aversion from inequity aversion.
5. Vulnerability to climate change is assumed to be constant.
6. Stern et al. (2006a, b) confuse the costs of climate change with the benefits of emission reduction.

The *Stern Review* was also criticized for overestimating the impact of climate change by cherry picking (Pielke, 2007); for underestimating the costs of emission reduction (Tol and Yohe, 2006, 2007a; Anderson, 2007); for incomplete and inconsistent documentation (Weitzman, 2007); and generally for violating the rules of good practice in policy analysis (Cole, 2007). We will not deal with these issues here. Some papers claim that the *Stern Review* underestimated the impacts of climate change (Neumayer, 2007; Spash, 2007; Sterner and Persson, 2007), while other papers argue that human-induced climate change is not real (Byatt et al., 2006; Carter et al., 2006). We address neither position, because we do not see any empirical support for either claim. To be fair, we note that the Stern team has also published a number of rebuttals (Dietz et al., 2007a, b; Hamid et al., 2007; Stern and Taylor, 2007), but we are not convinced their arguments have undercut any of the conclusions offered below.

Section 2 presents our simple and transparent model.[3] It was designed specifically for this paper to explore the robustness of the advertised results and to examine the six sources of concern noted above. It begins with a replication of the main elements of the impact analysis of the *Stern Review*, and it thereby demonstrates that the model is calibrated to give the same headline conclusions. It is here that we place our analysis squarely in realm created by the Stern team.[4]

[1] The *Stern Review* thereby violates the discounting procedures of HM Treasury. A postscript was released later (Stern et al., 2006b) with a limited sensitivity analysis. It received no media attention even though the analysis clearly demonstrates the fragility of the earlier conclusions.

[2] Neither the pure rate of time preference nor the rate of risk aversion can be directly observed. However, the consumption rate of discount can be observed, and it is a function of the pure rate of time preference and the rate of risk aversion.

[3] Simplicity and transparency are, of course, in the eye of the beholder. All equations and parameter assumptions of our model are included in the current paper.

[4] All of these estimates clearly depend on the baseline; that fact has been known for some time. We do not deviate from the baseline adopted by the Stern team not because we do not admit to this sensitivity. We anchor our analysis on that baseline for the sake of transparency and rigor so that the differences we observe are clearly the result of our experiments with critical parameters and not arifacts of changing calibration. We do not report a sensitivity analysis on the baseline we share with the *Stern Review* because little insight is gained. A different baseline implies that climate change would be different, that overall vulnerability as well as the pattern of vulnerability would be different, and that the numeraire (development without climate change) would be different. Decomposition methods have yet to be developed for integrated assessment models, while standard methods are linear and therefore not much use—alternative baselines are very different, and IAMs are non-linear.

In Section 3, we report the results of our systematic sensitivity analyses. Our results show that the *Stern Review's* conclusions are highly sensitive to a number of fundamental factors. Some of the factors that we explore, like the discount rate and the aversion to risk and/or inequality, are reflections of decision-makers' preferences. The sensitivity of damage estimates to these parameters cannot, therefore, be the sole basis of our concern that the Stern results are misleading. These sensitivities simply indicate the importance of the specific normative views adopted by the Stern team about how the world should conduct its policy analysis of what is essentially a long-term public goods problem. The Stern team had every right to pick whatever perspective it wanted, and they did offer some of their own sensitivity analysis of these factors in Stern et al. (2006b)—not in the *Review*, itself, but in the postscript that was posted on the website after the *Review* was released in October of 2006.

We also explore the sensitivity of the *Review*'s damage estimates to other factors, like the choice of time horizon, the treatment of evolving vulnerability across the globe in Section 3, and the claimed value from mitigation efforts. We find comparable sensitivities, and they, in turn, lead us to expressing a deep concern about the tendency to dismiss large variances that can be attributed to internal inconsistencies in the underlying analysis, modeling choices about how to construct damage estimates, and/or assumptions about how the planet's economic systems will develop and exploit adaptive capacity. It is here that we find reasons to think that the results reported in the *Stern Review* can be extraordinarily misleading if the sources of these sensitivities are not fully appreciated. Concluding summary remarks occupy Section 4.

2. The model

The model used here is simple and transparent. There are three regions: poor, middle income, and rich with initial average per capita incomes (denoted by y_r where the subscript r identifies the region) of \$350, \$3500 and \$35,000, respectively. Per capita income grows at rate $g_{r,t}$ where t denotes time and changes according to

$$g_{r,t} = 0.02\left(1 + \ln\frac{35000}{y_{r,t}}\right) \tag{1}$$

Eq. (1) ensures that the poorer regions grow faster and that growth gradually slows. Annual incomes stabilize everywhere at \$95,140 per capita, but not before 2500. The assumption of income convergence is consistent with the IPCC SRES scenarios (Nakicenovic and Swart, 2000) but not with the then current observations reported in Barro and Sala-i-Martin (1992). The *Stern Review* also assumes that developing countries catch-up with developed economies, and that per capita income growth slows down in the more remote future.

There are initially 2 billion poor people, 3 billion middle-income people, and 1 billion rich people on the planet. Population grows at rate p_r:

$$p_{r,t} = \max\left\{0, 0.005\ln\frac{35000}{y_{r,t}}\right\} \tag{2}$$

for the poor and middle-income regions. This ensures that the population of the poor region grows faster than in the middle-income region. The population of the rich region is assumed to be stationary, and so world population stabilizes at 9.2 billion in 2080. The *Stern Review* assumes a similar pattern of regional population growth and eventual stabilization.

There are three climate scenarios. They are all anchored, in the first period, by global mean temperature that is 0.7 °C above pre-industrial levels. Carbon dioxide emissions and concentrations are the same in the three scenarios. Without abatement policy, concentrations rise to 957 ppm in 2200, not inconsistent with the A2 scenario that underlies the *Stern Review*. In the low climate scenario, global mean temperature is initially climbing at 0.25 °C per decade (the warming between 1991–1995 and 2001–2005) but the pace slows by 1% per year. By 2100, global mean temperature is 2.3 °C higher than pre-industrial levels. In the middle scenario, global mean temperatures climb at 0.30 K per decade initially, but the pace of warming now slows by 0.5% per year. As a result, the global mean temperature in 2100 is 3.1 °C above pre-industrial levels and another 1.4 °C higher by 2200. In the high climate change scenario scenario, warming begins at 0.40 °C per decade and slows by only 0.1% per year so that global mean temperature is 4.5 °C higher than pre-industrial levels by 2100. The range of warming is typical of other published results given an assumption that the middle scenario has a likelihood weight of 0.70 while the other two scenarios share the remaining 30% probability. The assumed warming and its range is very similar to the scenarios used by the *Stern Review*.

Regional vulnerability to the impacts of climate change, denoted v_r below, is quadratic in the global mean temperature and anchored so that a 3 °C warming above pre-industrial levels leads to damage of 1.0% of GDP in the rich region, 3.3% in the middle-income region, and 5.6% in the poor region, respectively. These assumptions are broadly in line with estimates of the economic impacts of climate change authored by Smith et al. (2001). These estimates are based on the same literature used to calibrate the *Stern Review*, and also the shape of the damage function is similar.

The *Stern Review* expresses the impact of climate change in terms of change in the Balanced Growth Equivalent (BGE) of economic futures with and without associated damages. The BGE is a previously obscure but theoretically valid welfare measure defined implicitly by Mirrlees and Stern (1972) as α in

$$\sum_{t=0}^{T} U(\alpha(1+g)^t)\frac{P_t}{(1+\rho)^t} = \sum_{t=0}^{T} U(y_t)\frac{P_t}{(1+\rho)^t} = \sum_{t=0}^{T} U\left(y_0\prod_{t'=0}^{t}(1+g_t)\right)\frac{P_t}{(1+\rho)^t} \tag{3}$$

where U is some per capita utility function, P is population, ρ is the utility discount rate, y_0 is initial per capita income, g_t is the actual growth rate, and $t = 0,1,\dots,T$ denotes time. There are two unknown parameters on the left-hand side of (3): α, the BGE and g, the balanced growth rate. There are therefore infinitely many solutions to (3), but an intuitive one would be to set $\alpha = y_0$. Under that assumption, Eq. (3) essentially defines the net-present-welfare-equivalent balanced growth path g.

The BGE itself is not very interesting until one considers the BGE of an alternative stream of future incomes according to

$$\sum_{t=0}^{T} U(\alpha'(1+g)^t)\frac{P_t}{(1+\rho)^t} = \sum_{t=0}^{T} U(\alpha(1-\gamma)(1+g)^t)\frac{P_t}{(1+\rho)^t} = \sum_{t=0}^{T} U(y'_t)\frac{P_t}{(1+\rho)^t} \tag{4}$$

The relative change in the BGE, γ, summarizes the difference between two income streams in a single number. This was first suggested by Hammond and Kennan (1979).

Mirrlees and Stern (1972) and Hammond and Kennan (1979) only consider one region, and ignore uncertainty. However, the BGE can readily be generalized to multiple regions and uncertainty about future incomes and populations, as follows:

$$\sum_{r=1}^{R}\sum_{t=0}^{T} U(y_{r,0}(1+g)^t)\frac{P_{r,t}}{(1+\rho)^t} = \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T} U(y_{s,r,t})\frac{P_{r,t}}{(1+\rho)^t}, \quad \sum_{s=1}^{S}\omega_s = 1 \tag{5}$$

where $r = 1,2,\dots,R$ denotes the region, $s = 1,2,\dots,S$ denotes the state of the world, and ω_s denotes its probability. The growth rate g is now balanced over time, between regions, and across scenarios. Similarly, the change in BGE (i.e., ΔBGE) is thus balanced. Presumably, per capita income is known in period 0. If not: $y_{r,0} = \sum_{s=1}^{S}\omega_s y_{s,r,0}$.

We essentially replaced the actual growth path per capita with its equivalent steady-state growth path in Eq. (3), but we kept population as it is. If not, the solution would involve determining the value for an additional unknown (i.e., steady-state population growth). Following the same logic, Eq. (5) has the same steady-state economic growth for each region, but allows for different population growth in different regions. This also allows us to account for uncertainty about future populations, as follows:

$$\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T} U(y_{r,0}(1+g)^t)\frac{P_{s,r,t}}{(1+\rho)^t} = \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T} U(y_{s,r,t})\frac{P_{s,r,t}}{(1+\rho)^t} \tag{6}$$

and ΔBGE follows immediately. Now, defining $y'_{s,r,t} = y_{s,r,t}(1-\gamma_{s,r,t})$, we have

$$\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T} U(y_{r,0}(1-\gamma)(1+g)^t)\frac{P_{s,r,t}}{(1+\rho)^t} = \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T} U(y_{s,r,t}(1-\gamma_{s,r,t}))\frac{P_{s,r,t}}{(1+\rho)^t} \tag{7}$$

Phrased in this way, ΔBGE summarizes a series of welfare losses that vary over time between regions and across scenarios into a single number. This is a useful indicator.

Note that ΔBGE is calculated in two steps in the process described above, but this is not necessary in all cases. If $U(y(1-\gamma)) = U(y)+U(1-\gamma)$ (because $U(y) = \ln(y)$ for example), then Eq. (7) becomes

$$\begin{aligned}\ln(1-\gamma)\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}\frac{P_{s,r,t}}{(1+\rho)^t} &= \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}\ln(1-\gamma_{s,r,t})\frac{P_{s,r,t}}{(1+\rho)^t} \\ &+ \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}\ln(y_{s,r,t})\frac{P_{s,r,t}}{(1+\rho)^t} \\ &- \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}\ln(y_0(1+g)^t)\frac{P_{s,r,t}}{(1+\rho)^t}\end{aligned} \tag{8}$$

The last two terms of the right-hand side cancel to produce the equivalent of Eq. (6). Note that Eq. (8) defines γ as the weighed sum of the $\gamma_{s,r,t}$ with population, discount factor, and scenario probability as weights. Per capita income is not considered. The controversial assumption that all regions are on the same balanced growth path conveniently drops out of the equation, as well.

Also, if $U(y(1-\gamma)) = U(y)f(1-\gamma)$ (taking $U(y) = y^{1-\eta}/1-\eta$ for a second illustration), then Eq. (7) becomes

$$\begin{aligned}f(1-\gamma) &= \frac{\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}U(y_{s,r,t}(1-\gamma_{s,r,t}))(P_{s,r,t}/(1+\rho)^t)}{\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}U(y_{r,0}(1+g)^t)(P_{s,r,t}/(1+\rho)^t)} \\ &= \frac{\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}U(y_{s,r,t}(1-\gamma_{s,r,t}))(P_{s,r,t}/(1+\rho)^t)}{\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}U(y_{s,r,t})(P_{s,r,t}/(1+\rho)^t)}\end{aligned} \tag{9}$$

The last step follows from Eq. (6). Note that, as a consequence, one does not need to calculate the balanced growth rate, or indeed the balanced growth equivalent, in order to calculate the change in the balanced growth equivalent. One does not need to assume that all regions are on the same balanced growth path. As in Eq. (8), γ is the weighed sum of the $\gamma_{s,r,t}$, but per capita income is part of the weights in Eq. (9).

We define certainty- and equity-equivalent annuity (CEEA) as follows:

$$\sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}U(y_{s,r,t}(1-\gamma)(1+g)^t)\frac{P_{s,r,t}}{(1+\rho)^t} = \sum_{s=1}^{S}\omega_s\sum_{r=1}^{R}\sum_{t=0}^{T}U(y_{s,r,t}(1-\gamma_{s,r,t}))\frac{P_{s,r,t}}{(1+\rho)^t} \quad (10)$$

It is obvious that the CEEA equals the ΔBGE for the utility functions discussed above. The CEEA has two minor advantages. Firstly, one would not be tempted to compute it in two steps, or be led to think that different regions are assumed to grow at the same pace. Secondly, it calls things by its proper name. The left-hand-side and the right-hand side of Eq. (10) differ in one way only. On the right, the income loss γ has three indices; on the left, it has none. That is, the income loss is averaged over time (annuity), across scenarios (certainty-equivalent) and between countries (equity-equivalent).

For the chosen parameters, $\gamma = 5.3\%$—very close to Stern et al. (2006a, b). If we add 4% of GWP to the benchmark damage, and add a 10% scenario with warming escalating to 5.9 °C in 2100 and 14.4 °C in 2200, then $\gamma = 20.1\%$, close to the *Stern Review*'s upper bound of 20% for a similar change in assumptions. Although our model is much simpler and therefore more transparent than the PAGE2002 model used in the *Stern Review*, it has essentially the same assumptions and the same results. Below, we test the robustness of the results to changes in the assumptions.

3. Results

The simple model allowed us easily to perform a number of sensitivity experiments. The results are displayed in the various panels of Table 1. This section refers systematically to those panels as it discusses their sources and their implications. Some of the sensitivities have been explored in other papers. This is particularly the case for the pure rate of time preference. Our analysis does not add much to this debate. However, we do show that the sensitivity of the results to other parameters, hardly discussed in the literature, is as large as the sensitivity to the discount rate.

3.1. Base assumptions

Fig. 1 shows the damages per region and scenario. In 2200, impacts range from 1% of GDP in the low scenario in the rich region, to 40% of GDP in the high scenario in the poor region.[5] Fig. 1 also shows that the CEEA equals 5.3%. While this aggregate estimate conforms to the Stern team's most modest damage estimates, we have reconfirmed that aggregate numbers, including Stern's, always hide many details. Fig. 1 further shows the certainty-equivalent annuity *per region*—an annuity that does not include summing over the regions. This is 7.4% of GDP for the poor region, 4.1% for the middle-income region, and only 1.2% for the rich region. Comparing the two sets of damage measures underlines the point that a climate policy based on the CEEA computed in the *Review* is equivalent to an implicit income transfer from the rich region to poor region. Conversely, unabated climate change implies a transfer from the poor region to the rich region. One should wonder whether other types of income transfers would not be more effective or more desirable, but that is another story; see Tol (2003), Yohe (2003) and Tol and Yohe (2006) for some preliminary thoughts.

3.2. Pure rate of time preference

Stern et al. (2006a, b) use a pure rate of time preference (PRTP) of $\rho = 0.1\%$ per year. Philosophers have long argued that the PRTP should be zero, but most people and their governments use much higher values.[6] Indeed, Stern et al. (2006a, b) argue for a zero PRTP, but justify their slightly higher number with the assumption that there is a 10% probability that *Homo sapiens* will go extinct in the 21st century (p. 161). The species has survived for thousands of centuries and is more able and abundant than ever, so the Panel A of Table 1 reports results for an even lower discount rate consistent with a 1% probability of survival. Given the associated pure rate of time preference of 0.01, the CEEA is 5.4%—only a small increase from the base case. However, if we use a PRTP of 1% or 3%, the CEEA falls to 3.6% or 1.6%, respectively. Note that OECD governments typically use a PRTP of around 3% (Evans and Sezer, 2004). Moreover, using different discount rates for different policies would induce inconsistencies (e.g., Pearce, 2003).

3.3. Time horizon

The PRTP determines the relative weight that is placed on future damages. The lower the PRTP, the more the future matters and the farther one should look into the future. Stern et al. (2006a, b) have chosen a time horizon of 200 years. This is peculiar, since the utility discount factor is still 82% after 200 years of discounting at 0.1% per year. Stern et al. (2006a, b, p. 162) assume that impacts beyond 2200 are zero. We adopt the same assumption in the rest of the paper. We note in Panel B of Table 1, however, that decisions about the time horizon matter. The CEEA increases as we look further into the future, to 8.9% if we add a century, 20.9% if we add two centuries, and 44.9% if we look as far as the year 12,000. The discount factor goes to zero only around then, so it takes the CEEA something on the order of 10,000 years to converge to its true value. Put another way, Panel B indicates that the 200 year truncation built into Stern et al. (2006a, b) has produced a numerical error of an order of magnitude.

Table 1 also shows the CEEA for shorter time horizons. For a 50 year horizon, the CEEA falls to 1%. Stern et al. (2006a, b) use a 2050 horizon for the costs of emission reduction and reports a best guess of 1% of GDP. They use this best guess, which is lower than the certainty-equivalent, in their cost–benefit comparison for mitigation; and this is a problem. Put another way, had Stern et al. (2006a, b) used the same 2050 time horizon for costs and benefits, and had their treatment of uncertainty been internally consistent, then their preferred policy would not have passed their crude cost–benefit test.

For time horizons beyond 2050, Stern et al. (2006a, b) do not have the data to do a cost–benefit analysis, although one can reasonably assume that the costs of climate change escalate faster than the costs of emission reduction. Extending the time horizon

[5] Following Stern et al. (2006a, b), we assume that economic impacts have no effect on emissions. The effect of this assumption can be gleaned from the stabilization exercise below.

[6] See Arrow (2007) and Portney and Weyant (1999) for a discussion on the discount rate in climate policy; and the many references in the introduction for a discussion on the discount rate in the *Stern Review*.

Table 1
Results of sensitivity analysis for various parameters against a based case calibrated to the *Stern Review* baseline.

(1) PRTP	(2) CRRA	(3) RIEA	(4) Horizon	(5) Concentration	(6) Vulnerability	(7) CEEA
Panel A: Sensitivity to the pure rate of time preference (values noted in column (1) headed "PRTP")						
0.01	1	0	2200	957	Constant	−5.4
0.1	1	0	2200	957	Constant	−5.3
1	1	0	2200	957	Constant	−3.6
3	1	0	2200	957	Constant	−1.6
Panel B: Sensitivity to the time horizon (values noted in column (4) headed "horizon")						
0.1	1	0	2050	957	Constant	−1.0
0.1	1	0	2100	957	Constant	−2.3
0.1	1	0	2200	957	Constant	−5.3
0.1	1	0	2300	957	Constant	−8.9
0.1	1	0	2400	957	Constant	−15.0
0.1	1	0	2500	957	Constant	−20.9
0.1	1	0	3000	957	Constant	−36.0
0.1	1	0	5000	957	Constant	−42.6
0.1	1	0	12000	957	Constant	−44.9
Panel C: Sensitivity to the rate of risk aversion (values noted in column (2) headed "CRRA")						
0.1	0.5	0	2200	957	Constant	−6.1
0.1	0.75	0	2200	957	Constant	−5.7
0.1	1	0	2200	957	Constant	−5.3
0.1	1.25	0	2200	957	Constant	−4.6
0.1	1.5	0	2200	957	Constant	−3.7
0.1	1.75	0	2200	957	Constant	−2.7
0.1	2	0	2200	957	Constant	−1.8
0.1	2.25	0	2200	957	Constant	−1.2
0.1	2.5	0	2200	957	Constant	−0.8
Panel D: Sensitivity to the rate of inequity aversion (values noted in column (3) headed "RIEA")						
0.1	1	0	2200	957	Constant	−5.3
0.1	1	0.5	2200	957	Constant	−4.6
0.1	1	1	2200	957	Constant	−3.9
0.1	1	1.5	2200	957	Constant	−3.1
0.1	1	2	2200	957	Constant	−2.4
Panel E: Sensitivity to variable vulnerabilities (condition noted in column (6) headed "vulnerability")						
0.1	1	0	2200	957	Constant	−5.3
0.1	1	0	2200	957	Falling	−1.6
Panel F: Sensitivity to various stabilization targets (atmospheric concentration limits in column (7) headed "concentration")						
0.1	1	0	2200	957	Constant	−5.3
0.1	1	0	2200	750	Constant	−3.8
0.1	1	0	2200	700	Constant	−3.4
0.1	1	0	2200	650	Constant	−3.0
0.1	1	0	2200	600	Constant	−2.6
0.1	1	0	2200	550	Constant	−2.2
0.1	1	0	2200	500	Constant	−1.7
0.1	1	0	2200	450	Constant	−1.3
0.1	1	0	2200	400	Constant	−0.8

Changes in the certainty-equivalent and risk equivalent annuity are reported in column (7) headed "CEEA".

would therefore favour more stringent emission abatement. However, if the chosen time horizon (e.g., year 2200) is earlier than the convergence time horizon (i.e., year 12,000), the recommended policy is as arbitrary as the choice of the time horizon.

3.4. *Rate of risk aversion*

Stern et al. (2006a, b) use a constant relative risk aversion (CRRA) of unity. This is a standard assumption and mathematically convenient. Empirical evidence suggests that the CRRA is in fact a bit higher (Evans and Sezer, 2004), but recent estimates derived by Chetty (2006) from the wage elasticity of labor supply across the developed world suggest an upper bound of around 2. We replace the utility function in Eq. (3) with the more general

$$U(y_{r,t}) = \begin{cases} \dfrac{y_{r,t}^{1-\eta}}{1-\eta}, & \eta \neq 1 \\ \ln y_{r,t}, & \eta = 1 \end{cases} \tag{11}$$

where η is the CRRA. Although more general, this utility function does not capture the latest thinking in welfare economics. Particularly, a single parameter η measures risk aversion, inequality aversion within and between jurisdictions, and consumption smoothing over time (e.g., Amiel et al., 1999).

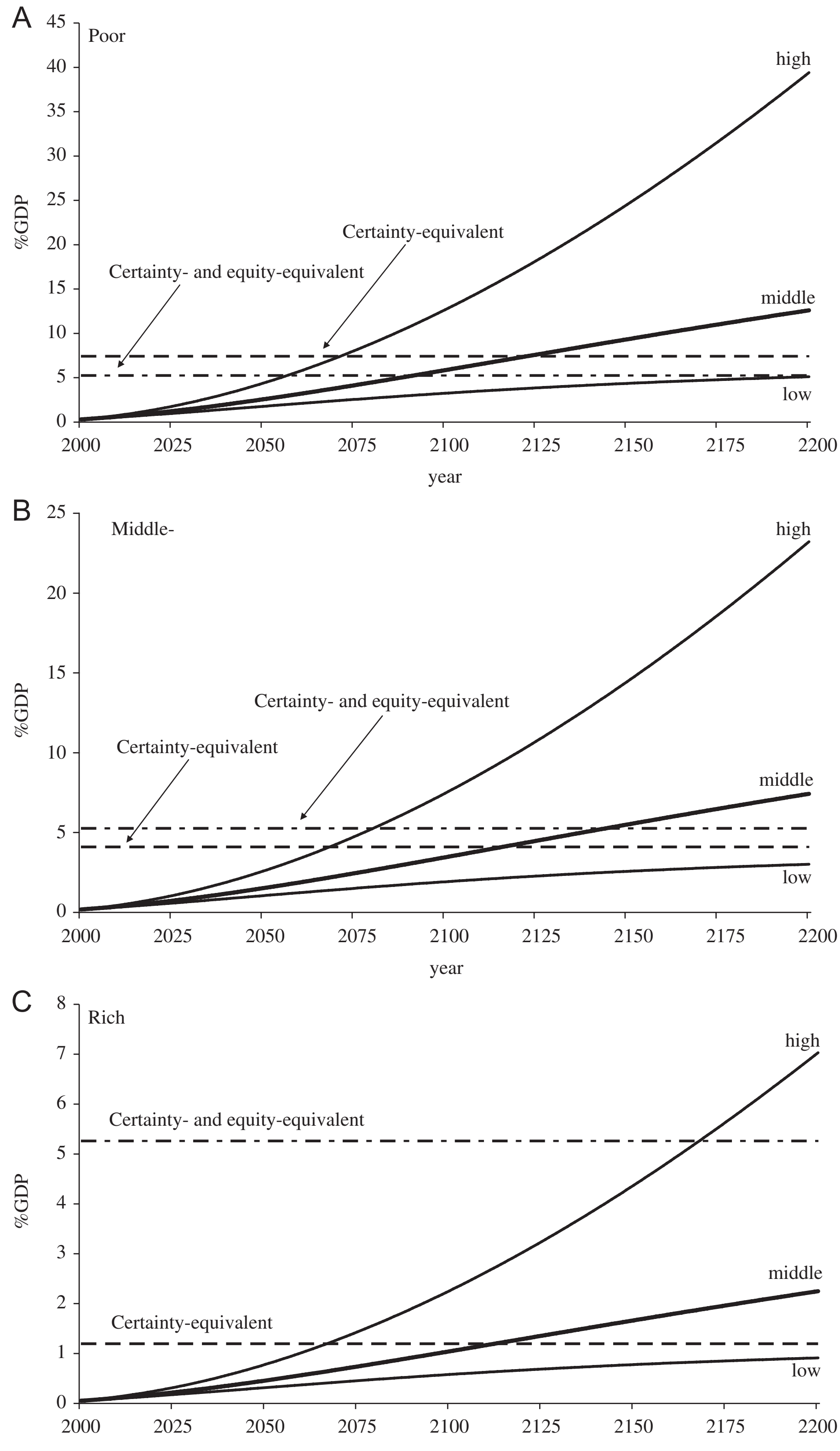

Fig. 1. Economic damages in (A) the poor, (B) middle-income, and (C) rich regions along the high, middle and low climate scenarios. The region-specific certainty-equivalent and the global certainty- and equity-equivalent are shown as well.

The Panel C of Table 1 shows the results. The CEEA is increasing in the CRRA (and so climate damages fall). This is surprising at first. With a higher CRRA, more emphasis is placed on the high climate change scenario and on the higher impacts felt by the poor. However, the underlying scenarios assume rapid economic growth and convergence of per capita incomes. The latter effects dominate the former ones and so, for a CRRA of 1.5, the CEEA calibrated damage estimate falls to 3.7%. Contrary to their suggestion, the *Stern Review*'s CRRA of unity was not a conservative choice.

3.5. Rate of inequity aversion

The CRRA governs both the aggregation over scenarios and the aggregation over regions. That is, the rate of risk aversion therefore doubles as the rate of inequity aversion. This is awkward, so we generalize (3) to

$$\sum_{i=p,m,r}\sum_{t=2000}^{2200}\frac{\ln(y_{i,t}(1-\gamma))^{1-\zeta}}{1-\zeta}(1+\rho)^t = \sum_{j=l,m,h}\omega_j\sum_{i=p,m,r}\sum_{t=2005}^{2200}\frac{\ln(y_{i,t}(1-\delta_{i,t,j}))^{1-\zeta}}{1-\zeta}(1+\rho)^t \tag{12}$$

where ζ is the rate of inequity aversion (RIA) and logarithmic utility fixes CRRA at unity. If $\zeta=1$, the summation is replaced with a product. If $\zeta=0$, the welfare function reduces to the strict utilitarian welfare function. The welfare function in (12) is far from perfect, but it does allow one to express concern about the impacts of climate change on the distribution of income across the world.

Panel D of Table 1 shows the results. The same effect holds as above. The CEEA falls with increasing inequity aversion, because of the assumed rapid economic growth and income convergence. In contrast to what is suggested in the Stern Review, omitting equity weights does not necessarily bias the impact estimates downwards.

3.6. Vulnerability

Stern et al. (2006a, b) assume that vulnerability to climate change (i.e., damage expressed as a proportion of GDP at the benchmark warming of 3 °C above pre-industrial levels) is constant over time. At the same time, poorer regions are assumed to be more vulnerable than richer regions. As poorer regions get wealthier, though, should it not be the case that their vulnerabilities decline? To reflect an affirmative answer to this question on the basis of insight drawn from Yohe and Tol (2002), Adger (2006) and Tol and Yohe (2007a, b), we replaced the assumption of constant vulnerability v with

$$v_{r,t}=\max\left\{0.01,\ 0.01\left(1+\ln\frac{35000}{y_{r,t}}\right)\right\} \tag{13}$$

That is, we conservatively assume that vulnerability is constant (calibrated at 1% for a 3 °C warming) in the rich region, but we also assume that it falls persistently toward 1% as income in other regions grow. To be specific, benchmark vulnerability begins in 2000 at 3.3% and 5.6% for middle and low income regions, respectively, but falls endogenously according to Eq. (13) with economic progress. Panel E of Table 1 shows the result of this single but perhaps more realistic alternative; the CEEA falls to 1.6%. That is, assumptions about future vulnerability to climate change are numerically as important as the choice of the pure rate of time preference.

Although we present the results here in a positive, what-if manner, the policy implications go beyond a benefit-cost analysis of greenhouse gas emission reduction. Not only is vulnerability not constant, it is not exogenous either. Targeted development or adaptation policies could help to reduce vulnerability to climate change, and in certain circumstances may be a cheaper and more effective route to reducing the impacts of climate change (Tol, 2005).

3.7. Stabilization

Stern et al. (2006a, b) equate the benefits of climate policy with the impacts of climate change. As climate policy can only avoid part of climate change, this is incorrect because mitigation will not completely eliminate damages. Indeed, this is a fundamental conclusion of the Fourth Assessment Report of the IPCC; see, for example, Bernstein et al. (2007). Panel F of Table 1 shows that our work is consistent with this conclusion by tracking baseline damage estimates for various mitigation strategies designed to limit atmospheric concentrations of greenhouse gases. In the baseline scenario, the 2200 temperature is consistent with a carbon dioxide equivalent concentration of 957 ppm. To define alternative mitigation pathways, we reduce this maximum in 50 ppm increments from 750 down to 400 ppm.[7] For 750 ppm, the CEEA falls to 3.7%; for 400 ppm, the CEEA falls to 0.8%. Notice, in fact, that the CEEA is roughly linear in the target concentration. For stabilization at 550 ppm, the benefit (i.e., the reduction in damages reflected by a correspondingly higher CEEA) is 3.1% rather than the 5.3% claimed by Stern et al. (2006a, b). Approximating the benefits of climate policy with the impacts of climate change is thus misleading, and would skew the benefit-cost analysis in favour of stringent action.[8]

4. Discussion and conclusion

We began this work by creating a simple and hopefully transparent multi-region model designed to support a straightforward exploration of the sensitivity of the damage estimates reported in the *Stern Review* to critical modeling and parametric assumptions. In support of this analysis, we provide a rigorous definition of (the change in) the Balanced Growth Equivalent for multiple regions that can accommodate diverse uncertainty about the future. We show that, for utility functions that display constant relative risk aversion (i.e., utility functions that are employed in most analyses of the welfare impacts of climate change including the *Stern Review*), this ΔBGE does not depend on the assumed path of economic growth (and thus whether this is balanced or not). In addition, we show that the ΔBGE equals the more intuitive certainty- and equity-equivalent annuity (CEEA) in these cases.

Our analysis reveals or confirms a number of shortcomings about the *Stern Review*. In four of the five sensitivity analyses, the impact calibrated to the baseline estimate of the *Stern Review* is at the top end of the range. In some cases, the *Review* authors are simply making value judgments about how the world should make decisions. Their high estimates can, therefore, be interpreted as simple reflections of choices that they had every right to make given the perspective that they had every right to assume. It is, though, interesting to note that their parameter choices were so extreme that it would have been difficult to produce higher damage estimates. That is, their damage estimates were quite insensitive to moving model parameters in directions that would make them increase. Table 1 shows, for example, that lower pure rates of time preference or lower measures of constant aversion to risk or inequality could have supported higher damages, but not by much. Moving the other direction, though, by assuming higher rates of time preference and greater aversion to uncertainty and inequality would have yielded dramatically smaller estimates—reductions in the neighborhood of 80% would be supported by equally reasonable choices for these "perspective parameters".

[7] We do this by increasing the decline rate of warming by the same fraction in all three scenarios, so that the middle scenario meets the target.

[8] Note that we do not do a benefit-cost analysis in this paper, and indeed none was done in the *Stern Review*. The CEEA would not be an obvious route to benefit-cost analysis. Instead, one would want to maximise the welfare functions (e.g. 5) that are used to define the CEEA.

Our results also display sensitivities to other modeling assumptions that lead us to be concerned that the high damage estimates reported in *Stern* are more than a justifiable product of consistent analyses that assume particular policy perspectives. As a result, we fear that the *Stern* results are misleading. The sensitivity analysis on the time horizon shows, for example, that the *Stern Review* did not report the economic impact of climate change accurately because the authors chose a time horizon that is not appropriate for their preferred discount rate. In this one case, our results suggest that the *Stern Review* underestimated the impact of climate change by a factor ten (given the assumptions made about other critical parameters like a pure rate of time preference set equal to 0.1%) by stopping the calculations at roughly 2200.

Even more misleading, we fear, was the assumption that vulnerability would be constant over the next 200 years. Surely vulnerability in the poorest countries will fall as adaptive capacity climbs with income (recall that the *Stern Review* sees rapid growth in these countries), and our analysis suggests a high degree of sensitivity to moving to something more reasonable in this regard. We show, for example, that simply assuming that the world's countries will be no more vulnerable than today's developed countries when their per capita incomes reach current developed country levels reduced damages by 80%. Table 1 indicates that this reduction is comparable to the effect of accepting a pure rate of time preference of 3%.

Finally, our results correct another misleading impression borne of the *Stern Review*—that the reported damage estimates represent the value of mitigation. They do not, of course, because mitigation will not eliminate all damages. Indeed, we report that an 80% reduction in damages could be expected if a 400 ppm mitigation target (calibrated in ppm of carbon dioxide equivalents) were achieved, and that a 60% reduction could be anticipated from a 550 ppm target.

These estimates of the value of mitigation are not trivial. They are on the same order of magnitude as the sensitivity of the damage estimates to essential modeling assumptions including the often cited sensitivity to a low pure rate of time preference. We have argued that some of these assumptions reflect policy perspective, and that is fine. Others, though, are reflections of modeling assumptions. To ignore their significance is misleading at best and dangerous at worst. Good decisions will be based on good information derived from transparent analyses that produce estimates whose sensitivities are clearly understood. Our work suggests that the *Stern Review* has not yet achieved that standard.

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