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 discounting time horizon, rates of risk and equity aversion used to compute certainty- and equity equivalent annuities, and presumed static regional vulnerability. 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, increase damage estimates by 900%. We also confirm the usual result that limiting atmospheric concentrations to specific benchmarks above 400 ppm cannot eliminate damages. Nonetheless, we applaud the *Stern Review* author team for reconfirming that the climate problem can productively be approached as an economic problem whose solutions can be explored with the tools of decision analysis.

Keywords: economics of climate change, certainty equivalent and equity equivalent annuity, relative risk aversion, equity aversion, pure rate of time preference

1. Introduction

The first media reports that were circulated prior to the release of the *Stern Review of the Economics of Climate Change* (Stern *et al.*, 2006) were dismissed quickly as journalistic hyperbole. The *Stern Review* was going to report the results of what was essentially to be a literature survey attached to some standard integrated modeling, and the numbers quoted in the press were clearly outside the range of conventional wisdom. A literature review could not have produced an outlier. Or could it? It turned out that the media reports on the *Stern Review* were largely accurate. 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 presented qualitative discussions of discussions of why the *Stern Review* is an outlier in earlier papers (Tol, 2006; Tol and Yohe, 2007, Yohe and Tol, 2007). Baer (2007), Byatt *et al.* (2006), Carter *et al.* (2006), Dasgupta (2006), Hope (submitted), Maddison (2006), Mendelsohn (2006), Nordhaus (2006), and Varian (2006) all added their own variations on the same theme, and Yohe (2006) presented a quantitative reconstruction of the *Stern Review*'s headlines - climate change damages of "5 to 20% of GDP, now and forever". Here, we report on the results of a similar but more extensive exercise designed explicitly to explore the roles of a small set of what turn out to be significant parameters using a model that was specifically constructed expressly to maximize transparency. Hope (2007) uses the PAGE model (which was also used by the authors of *Stern Review*) to the same purpose.

Critiques of the Stern estimates of the economic impacts of climate change can be summarized in a series of succinct statements:

1. Stern *et al.* (2006) use an extraordinarily low discount rate without reporting a sensitivity analysis.[1]
2. The *Stern Review*'s low discount rate does not match the equally low assumed rate of risk aversion.
3. Stern *et al.* (2006) do not separate risk aversion from inequity aversion.
4. The time horizon in the *Stern Review* is too short for the chosen discount rate.
5. Vulnerability to climate change is assumed to be constant.

Here, we will explore the ramifications of these statements in turn. Section 2 presents the model that was designed specifically for this paper to explore their significance in determining the advertised results. It begins with a replication of the main elements of the impact analysis of the *Stern Review*, and it is calibrated to give the same headline conclusion. In Section 3, we subject the conclusion to the systematic sensitivity analysis that is so sorely missed in the *Stern Review* and show that Stern's conclusions are highly misleading because they are so highly sensitive to these factors. Section 4 nonetheless

[1] The *Stern Review* thereby violates the discounting procedures of HM Treasury. A postscript was released later (Stern *et al.*, 2007) with a limited sensitivity analysis. It received no media attention even though the analysis clearly demonstrates the fragility of the earlier conclusions.

concludes with a message of appreciation to authors for their efforts to carry such heavy water.

2. The model

The model is simple and transparent. There are three regions: poor, middle income, and rich with initial average per capita incomes (denoted by y_r) of \$350, \$3500 and \$35000, respectively, and where the subscript r denotes region. Per capita income grows at rate $g_{r,t}$ where t denotes time and changes according to:

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

This ensures that the poorer regions grow faster and that growth gradually slows. Annual incomes stabilize everywhere at \$95140 per capita, but not before 2500.

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:

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

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.

There are three climate scenarios. They are all anchored, in the first period, by global mean temperature that is 0.7^{o}K above pre-industrial levels. In the low climate scenario, global mean temperature is initially climbing at 0.25K per decade (the warming between 1991-1995 and 2001-2005) but the pace slows by 1% per year. By 2100, global mean temperature is 2.3K higher than pre-industrial levels. In the middle scenario, global mean temperatures climb at 0.30K 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 3.1K above preindustrial levels and another 1.4K higher by 2200. In the high climate change scenario scenario, warming begins at 0.40K per decade and slows by only 0.1% per year so that global mean temperature is 4.5K 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 combination of population, income, and warming is similar to the A2 scenario 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 3K 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.

We measure impacts by their certainty-equivalent and equity-equivalent annuity (CEEA). The CEEA (denoted by γ) solves

$$(3) \qquad \sum_{i=p,m,r} \sum_{t=2000}^{2200} \ln\left(y_{i,t}(1-\gamma)\right)(1+\rho)^{-t} = \sum_{j=l,m,h} \omega_j \sum_{i=p,m,r} \sum_{t=2000}^{2200} \ln\left(y_{i,t}(1-\delta_{i,t,j})\right)(1+\rho)^{-t}$$

where ρ is the pure rate of time preference; ω is the scenario likelihood weight, indexed by j = *l*(ow), *m*(iddle), *h*(igh); and δ is climate change damage. The right hand side of Equation (3) computes the expected sum of discounted utility for all people living in the three regions across the three possible climate scenarios; the left hand side computes the proportional reduction in initial levels of per capita consumption for all people required to produce an equal sum of discounted utility.

The model is implemented in MicroSoft Excel; γ is solved by the in-built solver. For the chosen parameters, γ = 5.3% – very close to Stern *et al.* (2006).[2] If we add 4% of the GWP to the benchmark damage, and add a 10% scenario with warming escalating to 5.9K in 2100 and 14.4K in 2200, then γ = 20.1%, close to the *Stern Review*'s upper bound of 20%. Although our model is much simpler and 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.

Base assumptions

Figure 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.[3] Figure 1 also shows the certainty-equivalent and equity-equivalent annuity (the CEEA) of 5.3%. It is clear that this aggregate number hides many details. Figure 1 further shows the certainty-equivalent annuity *per region* – an annuity that does not

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[2] Note that Stern *et al.* (2006) claim to compute the balanced growth equivalent (BGE) introduced by Mirrlees and Stern (1972). The BGE equals the CEEA for $y_{i,t}=y_{i,0}(1+g_i)^t$, that is, the BGE is the CEEA for a constant rate of economic growth. This is unlikely. Here as in the *Stern Review*, economic growth is assumed to be rapid in the early decades and decelerates later. A balanced growth path would have a slower eradication of poverty. To compensate for that, the BGE is negative, not positive. In our calibration, the BGE is -179.4%, compared to the CEEA of +5.3%. Perhaps, the *Stern Review* computes the *difference* in the BGE between the scenario with and without climate change, as proposed by Hammond and Kennan (1979). To do this, the actual income at both the left hand side and the right hand side of Equation (3) need to be replaced by income along a steady state growth path. Note that, with logarithmic utility, the CEEA equals the difference in the BGEs. For other utility functions, this is not true. In that case, there is an ambiguity in the BGE about whether to use the global average steady state growth rate or the regional steady state growth rate. The CEEA does not have this ambiguity. We think the *Stern Review* computed the BGE *difference*, and as the Stern Review is limited to logarithmic utility, our CEEA is equivalent to what we think they did.

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

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 that a climate policy based on the CEEA computed in the *Review* would imply an income transfer from the rich region to poor region. Conversely, unabated climate change implies a transfer from poor region to 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.

Pure rate of time preference

Stern *et al.* (2006) use a pure rate of time preference (PRTP) of ρ=0.1% per year. Philosophers have long argued that the PRTP should be zero, but most people and their governments use much higher values. Indeed, Stern *et al.* (2006) 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. 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).

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.* (2006) have a time horizon of 200 years. This is peculiar, since the discount factor is still 82% after 200 years of discounting at 0.1% per year. Stern *et al.* (2006, p. 162) assume that impacts beyond 2200 are zero. In Panel C of Table 1, we explore this result further by extending the time horizon. 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 C indicates that the 200 year truncation built into Stern *et al.* (2006) 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.* (2006) use a 2050 horizon for the costs of emission reduction, with a best guess of 1% of GDP. Corrected for uncertainty in the same was as damages, these abatement costs would have been be higher. Put another way, had Stern *et al.* (2006) used the same time horizon for costs and benefits, their preferred policy would not have passed their crude cost-benefit test.

Rate of risk aversion

Stern *et al.* (2006) 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, 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 Equation (3) with the more general

(4) $$U(y_{r,t}) = \begin{cases} \frac{y_{r,t}^{1-\eta}}{1-\eta}, \eta \neq 1 \\ \ln y_{r,t}, \eta = 1 \end{cases}$$

where η is the CRRA.

The Panel B 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%.

Rate of inequity aversion

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

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

where ζ is the rate of inequity aversion (RIA) and logarithmic utility fixes CRRA at unity. If ζ=1, the summation is replaced with a product. 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.

Vulnerability

Stern *et al.* (2006) assume that vulnerability to climate change (i.e., damage expressed as a proportion of GDP at the benchmark warming of 3K 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 vulnerability declines? To reflect an affirmative answer to this question, we replaced the assumption of constant vulnerability v with

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

That is, vulnerability is constant (calibrated at 1% for a 3K warming) in the rich region, while it falls toward 1% with income growth in the other regions (beginning in 2000 with the 3.3% and 5.6% initial benchmarks for a 3^o K warming noted above). Panel E of Table 1 shows the result of this single but perhaps more realistic alternative; the CEEA falls to 1.6%.

Stabilization

Stern *et al.* (2006) 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. Panel F of Table 1 shows the result if we reduce climate change by implementing various mitigation strategies designed to limit atmospheric concentrations of greenhouse gases. In the baseline scenario, the 2200 temperature is equivalent to 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.[4] 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.* (2006).

4. Discussion and conclusion

It is too early to state with any confidence what the political implications of the *Stern Review* might be. Initial hopes in environmental corners that the Stern Review would be the definitive evidence in support of immediate and drastic emission reduction have proven to be naïve. Even in the UK, first Gordon Brown and later Tony Blair distanced themselves from their advisor, who duly resigned. A flurry of activity in the Congress of United States as well as the mention of the "serious challenge of global climate change" in the most recent State of the Union Address do not seem to have been the result of the *Review,* either. Indeed, a full two weeks after that address, the *Review* remained largely ignored across the United States even as the Intergovernmental Panel on Climate Change released its Working Group 1 report on the science.

Initial fears in some circles, that the *Review's* estimates were so suspect that they could only backfire and further polarize the debate have not materialized, either. Climate doubters and policy opponents have certainly continued their attempts to focus attention away from the fundamental messages that can be drawn from its literature survey if not its economic synthesis. They simply do not want further evidence to be put forward that the climate is changing faster than previously thought and that no specific temperature target can be guaranteed by holding atmospheric concentrations of greenhouse gases below any specific threshold. The *Stern Review* has not interrupted a perceptible, sometimes slow, and sometimes noisy march towards meaningful climate policy, but neither has it done anything to halt wild exaggeration from all sides.

Perhaps most productively, the *Stern Review* does seem to have induced a wider appreciation that climate change can be approached as an economic problem, and that

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[4] 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.

questions about the appropriateness of emission reduction can be illuminated (but not answered) with the tools of decision analysis. If that is true, then economists ought to be grateful even if the *Stern Review* itself failed to provide definitive support for the case.

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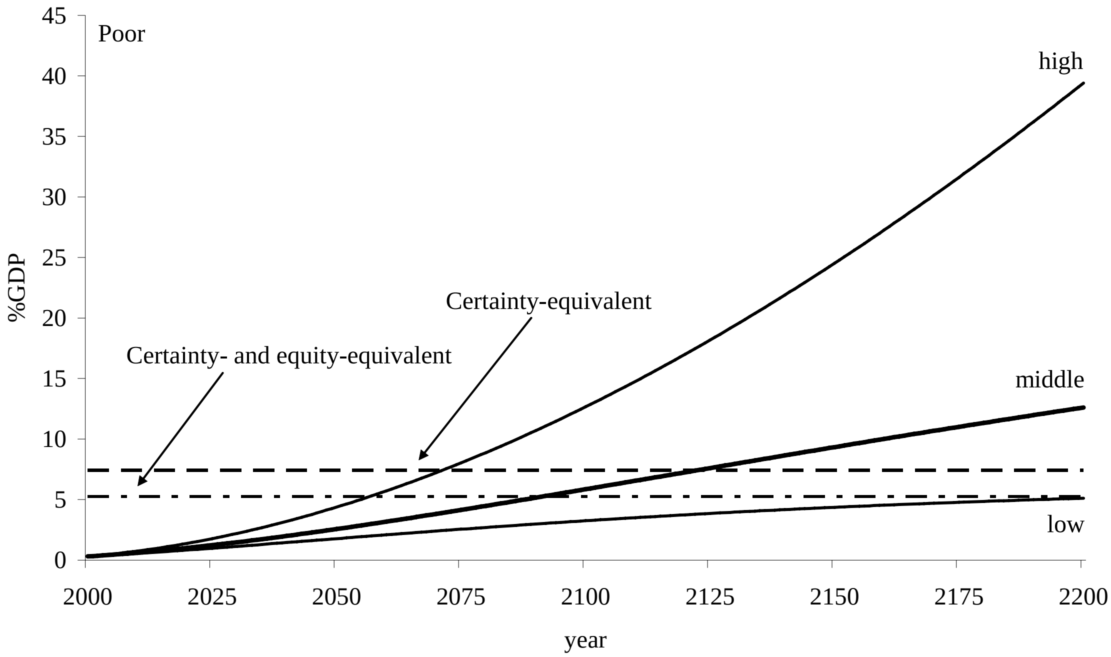
Table 1. Results of sensitivity analysis for various parameters against a based case calibrated to the *Stern Review* baseline. Changes in the certainty-equivalent and risk equivalent annuity are reported in column (7) headed “CEEA”.

(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 "Vunerability")						
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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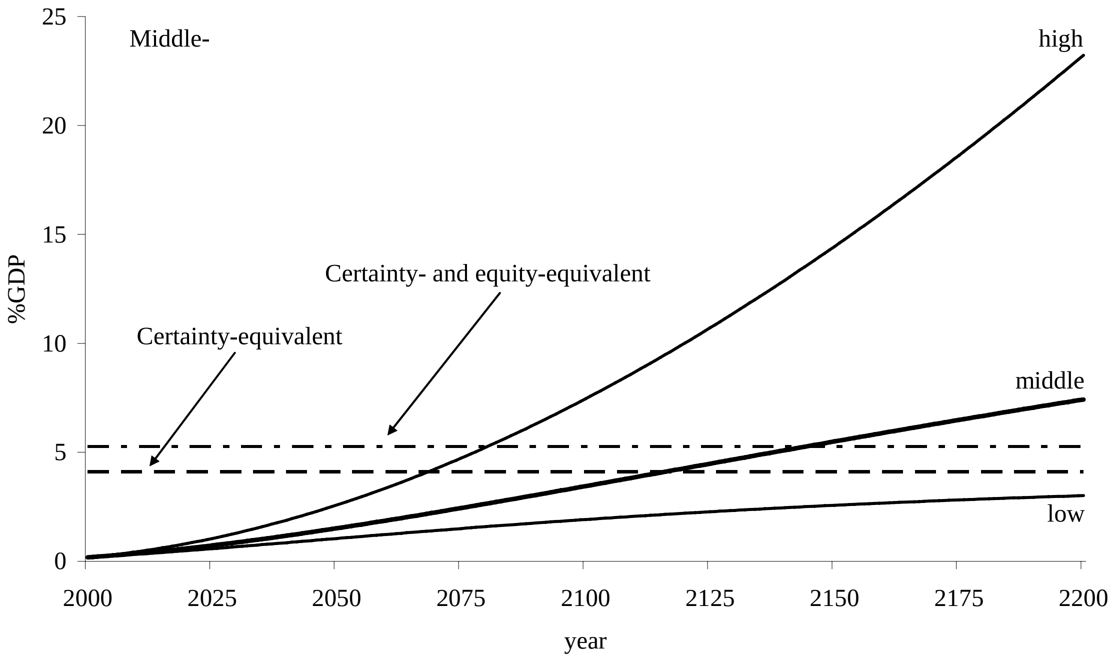
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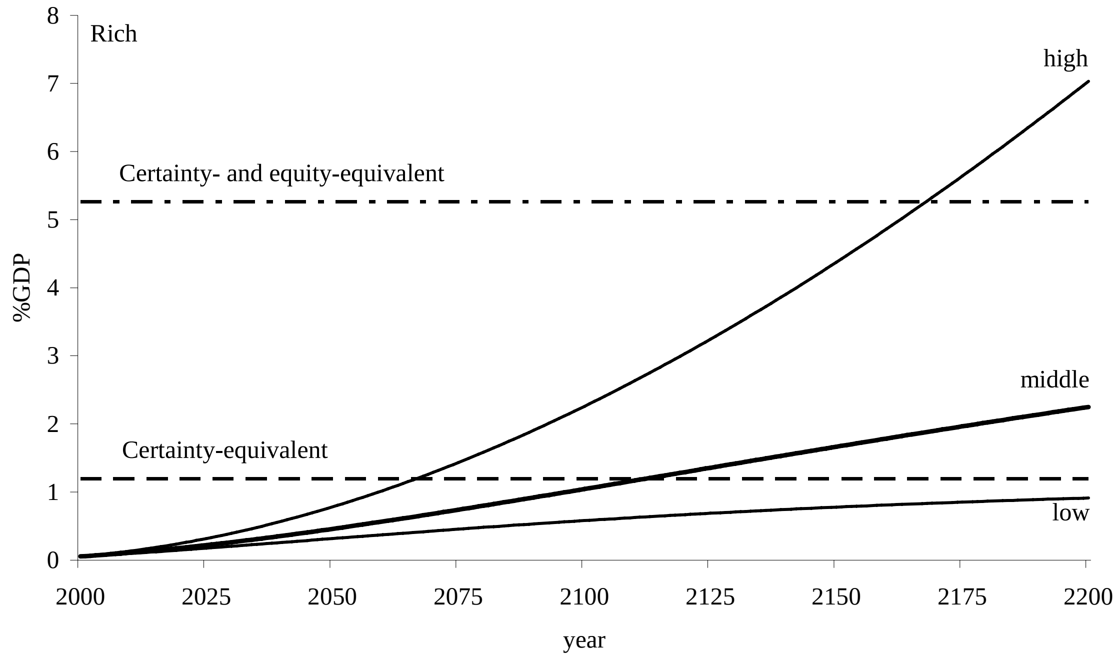

Figure 1. Economic damages in the poor (top panel), middle-income (middle panel) and rich (bottom panel) region for the high, middle and low climate scenario. The region-specific certainty-equivalent and the global certainty- and equity-equivalent are shown as well.

Working Papers

Research Unit Sustainability and Global Change

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Anthoff, D. and R.S.J. Tol (2007), *On International Equity Weights and National Decision Making on Climate Change*, **FNU-127** (submitted).

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