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The Impact of Climate Change on the Balanced Growth Equivalent: An Application of *FUND*

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Abstract The *Stern Review* added balanced growth equivalents (BGE) to the economic climate change research agenda. We first propose rigorous definitions of the BGE for multiple regions and under uncertainty. We show that the change in the BGE is independent of the assumed scenario of per capita income. For comparable welfare economic assumptions as the *Stern Review*, we calculate lower changes in BGE between a business as usual scenario and one without climate impacts with the model FUND than the *Stern Review* found with the model PAGE. We find that mitigation policies give even lower changes in BGE and argue that those policy choices should be the focus of the research effort rather than total damage estimates. According to our results, the current carbon tax should be below \$55/tC. Sensitivity analyses show that the *Stern Review* chose parameters that imply high impact estimates. However, for regionally disaggregated welfare functions, we find changes in BGE that are significantly higher than the results from the *Stern Review,* both for total damage as for policy analysis. With regional disaggregation and high risk aversion, we observe fat tails and with that very high welfare losses.

Keywords Impacts of climate change · Balanced growth equivalent · Stern Review

JEL Classification D63 · Q54

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1 Introduction

The *Stern Review on the economics of Climate Change* (Stern 2007) has caused substantial discussion, not least about the validity of the headline conclusion that climate change would cause a welfare loss equivalent to a permanent income loss of 5–20%. The initial responses of many economists (Arrow 2007; Dasgupta 2007; Mendelsohn 2006; Nordhaus 2007a,b; Pielke Jr 2007; Tol 2006b; Tol and Yohe forthcoming; Weitzman 2008; Yohe et al. 2007) focused on a variety of shortcomings of the research and the choice of the rates of pure time preference and risk aversion, but later reactions (Yohe and Tol 2007; Weitzman 2009) emphasized that the *Stern Review* has also brought renewed attention to the conceptual and moral difficulties of any economic appraisal of projects to limit climate change and its impacts.

This paper contributes in four ways to the ongoing debate about the conclusions of the *Stern Review*. First, this paper uses a different integrated assessment model and is thus a sensitivity analysis of the conclusions of the *Stern Review*. Second, we extend the analysis conducted by the *Stern Review* with a regionally disaggregated welfare module. Third, we not only calculate the difference between scenarios with and without climate impacts, but also evaluate specific policies in terms of changes in balanced growth equivalents. Fourth, we propose a rigorous definition of the balanced growth equivalent, which was lacking from the *Stern Review*.

The *Stern Review* diverged from the usual approaches of calculating the welfare impact of climate change employed in the literature (Pearce et al. 1996; Smith et al. 2001) in a number of ways. For one, it presented the results of its modeling exercise as changes in balanced growth equivalents (cf. Mirrlees and Stern 1972). Previous studies of climate change had presented economic damages as total impacts for a benchmark scenario (typically, the effect of a doubling of atmospheric carbon dioxide on today's population and economy).[1] The introduction of a new measure is certainly a refreshing move, but it makes comparison with previous results difficult. One could attempt to infer what the results from the *Stern Review* are in the metrics used in previous studies. In this paper, we choose the other direction: We use the welfare measure of the *Stern Review* but use the *FUND* model instead of *PAGE*. As such, this paper analyses how the results from the *Stern Review* depend on the specific assumptions made in the *PAGE* model. We also run the model with more combinations of input parameters than the *Stern Review* did, in particular, we investigate sensitivity to all IPCC SRES scenarios and more discounting schemes.

Mirrlees' and Stern's (1972) definition of the balanced growth equivalent is for a single decision maker and a constant population. The *Stern Review's* calculation of welfare measures is based on globally averaged per capita consumption and a growing population.[2] The *Stern Review* suggests that a more appropriate aggregation would take up regional data when deriving the welfare measure. Due to time constraints, the *Stern Review* seems not to have carried out those calculations. Here, we do use regional impacts, income, and population data to estimate changes in the balanced growth equivalent due to climate change.

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[1] The marginal impacts according to the *Stern Review* can be compared to previous studies. Tol (2008) does exactly that and finds that the *Stern Review* is an outlier.

[2] The text in the *Stern Review* is not clear on this point and (Stern 2008, p. 18) claims that the welfare function used for the *Stern Review* is a function of regional per capita consumption, but subsequent private communication (Simon Dietz) with the *Stern Review* team and a look at the source code that was used for the *Stern Review* and provided to us in the meantime confirmed that the *Stern Review* operated with global and not regional per capita consumption. Similar ambiguity is illustrated by the exchange on abatement costs between Anderson (2007), Dietz et al. (2007), and Tol and Yohe (2006, 2007a). See also Weyant (2008).

Finally, the *Stern Review* presented its results as differences between scenarios with no impacts from climate change at all and scenarios with climate change impacts. This cannot be regarded as an evaluation of policy options: there is no feasible policy option available today to avoid all climate change impacts in the future. A more meaningful result is obtained by looking at changes in welfare from feasible policy options. We here restrict the attention to one climate policy, described in Section 4.3.

Section 2 reviews the original definition of the balanced growth equivalent and shows our extension with non-constant populations, regional disaggregation, and uncertainty. While our derivations are relatively straightforward, they have not been presented before. The equations shown should avoid future ambiguities about the definition of the BGE and its extensions. Section 3 outlines the FUND model. Section 4 presents the numerical results. Section 5 concludes.

2 Balanced Growth Equivalent

2.1 Basic Concept

Mirrlees and Stern (1972) introduced the concept of a *balanced growth equivalent* (BGE) as a commodity measure of welfare. The thought was that when looking at policy proposals one could calculate the change in BGE for a particular policy and use that as a rough first estimate of whether further investigation of that policy would be warranted or whether the impact of that policy would be too small in the first place to warrant further research. The authors themselves suggest that there might be many broad economic policy options unexplored that would cause an increase of at least 1% in BGE and propose that those should attain more research time.[3] The BGE as a welfare measure has largely been ignored in the economics literature: only nine papers refer to Mirrlees and Stern (1972) according to the *Web of Science*, and none of these papers develops the BGE further or applies it. Stern (2007) appears to be the first application.

The following will briefly review the original concept with the notation used for this paper. Since we will later use a numerical model to run simulations, we use discrete time for the model, unlike the original specification of BGE. One key exercise of this paper is to compare the effects of various policy options with respect to climate change in terms of welfare changes. Policy choices are represented by ω. A specific policy choice ω could for example designate one specific carbon tax schedule. ω can stand for any policy out of all possible policy options, the numerical analysis later in the paper will restrict itself to a subset of policy options.

Let welfare for a specific policy ω be

$$W(\omega) = \sum_{t=0}^{T} U\left(C_{\omega,t}\right) P_t \left(1+\rho\right)^{-t} \tag{1}$$

where $C_{\omega,t}$ is *per capita* consumption at time t as it results from choosing policy ω, P is population, ρ is the utility discount rate, U is the utility function and T is the time up to which the analysis is carried out.

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[3] Note that the *Stern Review* and this paper use a different baseline than was originally suggested in Mirrlees and Stern (1972). They looked at improvements from the status quo, i.e., how a policy would improve the business as usual scenario. The *Stern Review* and this paper evaluate changes from a hypothetical world without climate change, where smaller changes (i.e., smaller damages) are better.

The BGE for policy ω is then defined by solving[4]

$$\sum_{t=0}^{T} U\left[\gamma(\omega)\,(1+\alpha)^t\right] P_t\,(1+\rho)^{-t} = W(\omega) \tag{2}$$

for $\gamma(\omega)$, with α being a constant growth rate (that later drops out when changes in γ are calculated). Note that $\gamma(\omega)$ is the initial level of per capita consumption that would give the same welfare as $W(\omega)$ if it grew at constant rate α.

For a standard constant-relative-risk-aversion utility function

$$U(C) = \begin{cases} C^{1-\eta}\,(1-\eta)^{-1} & \text{for} \quad \eta \neq 1 \\ \ln C & \text{for} \quad \eta = 1 \end{cases} \tag{3}$$

with η being the marginal elasticity of consumption, we have an explicit solution for γ

$$\gamma(\omega) = \begin{cases} \left[(1-\eta)\,W(\omega)\right]^{\frac{1}{1-\eta}} \left[\sum_{t=0}^{T} \frac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{W(\omega) - \ln(1+\alpha)\sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for} \quad \eta = 1 \end{cases} \tag{4}$$

Defining the relative change in BGE for two policies ω and ω' as $\Delta\gamma$, we get

$$\Delta\gamma := \frac{\gamma\left(\omega'\right) - \gamma\left(\omega\right)}{\gamma\left(\omega\right)} = \begin{cases} \left(\frac{W(\omega')}{W(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{W(\omega') - W(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for} \quad \eta = 1 \end{cases} \tag{5}$$

Note that $\Delta\gamma$ is independent of α, so that the change in BGE does not depend on the growth rate assumed in the calculation of a specific BGE—as long as the growth rates are the same for the two policy choices. The change in BGE thus expresses the difference between two scenarios as a constant change in relative consumption. It is an annuity, but an annuity that is based on the equivalence of net present welfare.

Note that population is (assumed to be) independent of the policy choice. If population is endogenous to the policy decision, one cannot use a welfare function like Eq. 1. See Blackorby and Donaldson (1984) and Blackorby et al. (1995).

2.2 Uncertainty

We now treat $W(\omega,\, s)$ as a random variable where $p(s)$ is the probability of state of the world s. Expected welfare then is

$$\mathrm{E}W\,(\omega) = \sum_{p} p\,(\omega, s) \sum_{t=0}^{T} U\left(C_{\omega,s,t}\right) P_t\,(1+\rho)^{-t} \tag{6}$$

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[4] Note that Eq. 7 in Chap. 6 in the *Stern Review* purports to define the BGE as used by (Stern 2007 p. 185) and thus would play the same role as our Eq. 2. Unfortunately, Eq. 7 in the review contains a number of errors: as printed, the function is not defined for $\eta = 1$, a balanced growth path is given by $C_{BGE}\,(1+g)^t$ and not the term $C_{BGE} + gt$ that is printed in the *Stern Review*, and finally this wrong term for consumption at time t is wrongly converted into utility by only putting C_{BGE} into the utility function and then adding gt to utility. Private communication with members of the *Stern Review* team (Simon Dietz, Nick Stern) and later comparison with the source code (also provided privately) used for the *Stern Review* assured us that these errors were only present in the text and that the equations used for the numerical results in the Stern Review did not contain these mistakes. Public availability of the source code and an errata (which we could not find) of the Stern Review could clear questions up for other readers of the *Stern Review*.

The certainty- and balanced growth equivalent (CBGE) is obtained be replacing $W(\omega)$ in (2) with expected welfare $\mathrm{E}W(\omega)$ as defined in (6). The CBGE can then be solved as:

$$\gamma_C(\omega) = \begin{cases} \left[(1-\eta)\,\mathrm{E}W(\omega)\right]^{\frac{1}{1-\eta}} \left[\sum_{t=0}^{T} \frac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{\mathrm{E}W(\omega) - \ln(1+\alpha)\sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for} \quad \eta = 1 \end{cases} \tag{7}$$

The CBGE is the initial level of per capita consumption, which, if it grows without any uncertainty at some constant rate α, gives the same level of welfare as the expected welfare for some policy ω as defined in (6). It is a combination of the certainty equivalence ideas put forward by Rothschild and Stiglitz (1970) with the balanced growth equivalent of Mirrlees and Stern (1972).

The change in the CBGE equals:

$$\Delta\gamma_C := \begin{cases} \left(\frac{\mathrm{E}W(\omega')}{\mathrm{E}W(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{\mathrm{E}W(\omega') - \mathrm{E}W(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for} \quad \eta = 1 \end{cases} \tag{8}$$

As before, the growth scenario α cancels.

2.3 Multiple Regions

In the final step, we introduce multiple regions. Assuming that the global welfare function is utilitarian, we have

$$W_E(\omega) = \sum_r \sum_{t=0}^{T} U\left(C_{\omega,t,r}\right) P_{t,r}\,(1+\rho)^{-t} \tag{9}$$

for a deterministic analysis and

$$\mathrm{E}W_E(\omega) = \sum_p p\,(\omega, s) \sum_r \sum_{t=0}^{T} U\left(C_{\omega,s,t,r}\right) P_{t,r}\,(1+\rho)^{-t} \tag{10}$$

for an analysis with uncertainty. Per capita consumption C and population P are now fed into the welfare function for each region r individually.

Replacing $W(\omega)$ in (2) with the deterministic welfare function that is disaggregated by regions $W_E(\omega)$ gives the equity- and balanced growth equivalent (EBGE) for a specific policy choice. This solves as:

$$\gamma_E(\omega) = \begin{cases} [(1-\eta)\, W_E(\omega)]^{\frac{1}{1-\eta}} \left[\sum_{t=0}^{T} \frac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{W_E(\omega) - \ln(1+\alpha) \sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for} \quad \eta = 1 \end{cases} \tag{11}$$

This combines the BGE concept with a measure of inequality very much like Atkinson (1970). The EBGE is the equally distributed (over the regions under consideration) initial per capita consumption, growing at a constant rate α that gives the same level of welfare as obtained for a specific policy choice ω from the welfare function defined in (9). Note that (11) has a different treatment for income difference between regions and between generations (cf. Tol 2002c).

The certainty, equity- and balanced growth equivalent (CEBGE) follows by replacing $W(\omega)$ in (2) with the expected welfare from the regional disaggregated welfare function as defined in (10) for some policy choice ω. This solves as:

$$\gamma_{CE}(\omega) = \begin{cases} [(1-\eta)\, \mathrm{E}W_E(\omega)]^{\frac{1}{1-\eta}} \left[\sum_{t=0}^{T} \frac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{\mathrm{E}W_E(\omega) - \ln(1+\alpha) \sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for} \quad \eta = 1 \end{cases} \tag{12}$$

which is the equally distributed (over the regions under consideration) initial per capita consumption growing without uncertainty at a constant rate α, that gives the same welfare level as the expected welfare of a certain policy choice ω as obtained by using (10).

From this it follows that the change in the EBGE between two policy options is

$$\Delta\gamma_E := \begin{cases} \left(\frac{W_E(\omega')}{W_E(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{W_E(\omega') - W_E(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for} \quad \eta = 1 \end{cases} \tag{13}$$

And the change in the CEBGE between two policy options is

$$\Delta\gamma_{CE} := \begin{cases} \left(\frac{\mathrm{E}W_E(\omega')}{\mathrm{E}W_E(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for} \quad \eta \neq 1 \\ \exp\left(\frac{\mathrm{E}W_E(\omega') - \mathrm{E}W_E(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for} \quad \eta = 1 \end{cases} \tag{14}$$

Note that in Eq. 14, the parameter η has a triple role. It is a measure of the curvature of the utility function—more specifically, the consumption elasticity of marginal utility—but it functions as the intertemporal substitution elasticity of consumption, the rate of risk aversion, and the rate of inequity aversion. Below, we refer to η as the rate of risk aversion.

Tol and Yohe (2007b) show a similar derivation, but use the term *certainty- and equity-equivalent annuity* because Eq. 14 distributes the impact equally over time, as well as over states of the world and over regions.

As stated in the introduction, we think that the *Stern Review* intended to report $\Delta\gamma_{CE}$ as defined in Eq. 14, but they seem to report $\Delta\gamma_C$ (8) instead.

3 The Model

FUND (the Climate Framework for Uncertainty, Negotiation, and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to a simple carbon cycle and climate model, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetarized in 1995 dollars and are modeled over 16 regions. Modeled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Link and Tol 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. Version 3.2, used in this paper, runs from 1,950 to 2,300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the welfare impacts of climate change are assumed to depend in part on the impacts during the previous year, reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical impacts and monetized welfare impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to provide a proper long-term perspective.

The period of 1950–1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk 1994). The period 1990–2000 is based on observations (http://earthtrends.wri.org). The 2000–2010 period is interpolated from the immediate past. The climate scenarios for the period 2010–2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). The period 2100–2300 is extrapolated.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions.

Emission reduction of carbon dioxide, methane, and nitrous oxide is specified as in Tol (2006a). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol 2005).

The scenarios of economic growth are perturbed by the effects of climatic change.[5] Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy caused by climate change. Methane and nitrous oxide are taken up in

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[5] Note that in the standard version of FUND population growth is also perturbed by climate change impacts. That particular feature was switched off in the runs for this paper because endogenous population changes cannot be evaluated with the kind of welfare function investigated, see discussion above.

the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on (Shine et al. 1990). The global mean temperature, T, is governed by a geometric build-up to its equilibrium (determined by the radiative forcing, RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature is derived by multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).

The climate welfare impact module, based on Tol (2002a,b) includes the following categories: agriculture, forestry, hurricanes, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages are triggered by either the rate of temperature change (benchmarked at 0.04°C/year) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol 2002b).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income.[6] The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline 1992). The value of emigration is set to be three times the per capita income (Tol 1995, 1996), the value of immigration is 40% of the per capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometer of dryland was on average \$4 million in OECD countries in 1990 (cf. Fankhauser 1994). Dryland value is assumed to be proportional to GDP per square kilometer. Wetland losses are valued at \$2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser 1994). The wetland value is assumed to have a logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol 2002a). Modeled effects of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behavior of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol 2002b).

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[6] Note that this implies that the monetary value of health risk is effectively discounted with the pure rate of time preference rather than with the consumption rate of discount (Horowitz 2002). It also implies that, after equity weighing, the value of a statistical life is equal across the world (Fankhauser et al. 1997).

The welfare impacts of climate change on coastal zones, forestry, hurricanes, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modeled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth) and heat-related disorders (with urbanization), or more valuable, such as ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol 2002b).

In the Monte Carlo analyses, essentially all parameters are varied. The probability density functions are mostly based on expert guesses, but where possible "objective" estimates were used. Parameters are assumed to vary independently of one another, except when there are calibration or accounting constraints. Details of the Monte Carlo analysis can be found on *FUND*'s website at http://www.fund-model.org.

4 Results

4.1 Scenarios

Stern (2007) present the impacts of climate change as the change in BGE between a baseline scenario with no climate change impacts and various scenarios with climate impacts. This is a measure of the overall damage of climate change. We present similar results but add more sensitivity analysis. In particular, we present results for alternative assumptions on discounting and risk aversion, and include four alternative socio-economic scenarios.

We refer to these runs as total damage estimates. Contrary to what Stern (2007) assert, these estimates of the total impact of climate change differ from the estimated benefits of climate policy. Avoiding all climate change is impossible, and emission abatement slows economic growth. We therefore present a second set of results where we evaluate specific carbon taxation policies and calculate the change in BGE (or any of the more complicated concepts) from a hypothetical scenario with neither climate change impacts nor any policy costs to a scenario with both policy costs of carbon taxation and impacts of climate change.

For any combination of socio economic scenario, pure rate of time preference, rate of risk aversion, uncertainty treatment and social welfare function, we calculated the BGE for two policy choices: One business as usual policy with no greenhouse gas taxation and the BGE for a particular policy choice. The latter is characterized as follows: Following a widely used practise, we impose a globally harmonized carbon tax on all regions. For the first time period, we search for a carbon tax rate that equals the social cost of carbon emissions, which in turn depends on the choice and parameterization of the social welfare function. We then increase this carbon tax with the world average discount rate in every time period.[7] We then present

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[7] Note that this ignores a number of complicated issues. First, the rate of increase of the optimal carbon tax would be less than the discount rate due to the decay of carbon in the atmosphere. In our experience the difference in results between the two approaches is marginal and would not have justified the significant computational complications associated with it. Second, there is an ongoing debate in the literature whether a harmonized carbon tax is optimal (cf. Chichilinisky and Heal 1994; Anthoff 2009), but we ignore these issues in this paper.

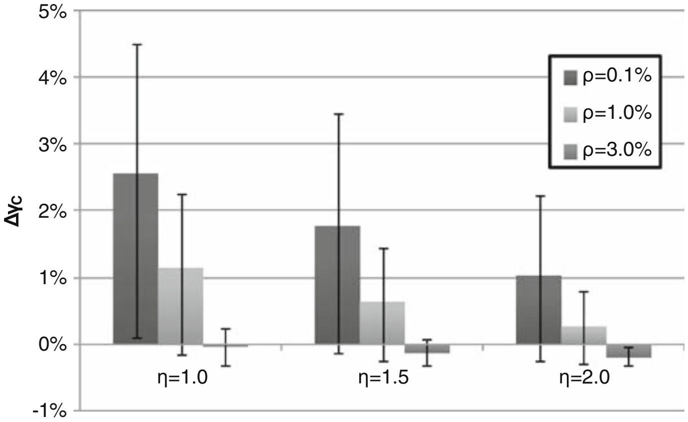

Fig. 1 Total damage as a change in BGE with a global welfare function

results as a change in the BGE from a run without any climate change impacts or policy costs to the BGE of one of the two policy choices.

In the following sections, we point out our key findings both for the total damage runs and the policy runs.

4.2 Total Damage

Figure 1 shows the loss of going from a scenario without climate change impacts to a business as usual policy (i.e., a scenario with no climate change mitigation but full impacts) in terms of change of CBGE for various pure rates of time preference, risk aversion and socio-economic scenario choices. Figure 1 shows the mean change in BGE over all socio-economic scenarios, with the minimum and maximum shown on the error bars. The numbers in this figure form the model sensitivity analysis to the results of the *Stern Review*.

In general, the numbers calculated by *FUND* tend to suggest lower total damages than the figures from the *Stern Review*, given apparently comparable welfare economic treatment.[8] One difference is that *FUND* has a time horizon of 2300, while *PAGE* stops at 2200. In the Stern Review impacts were assumed to be constant as a fraction of income for the time period 2200 to infinity and fully accounted for in the welfare function, whereas we assume no impacts after 2300. Note that the very questionable assumption of constant damages until infinity after the year 2200 is not a feature of the PAGE model, but was only implemented for the results of the *Stern Review*, as far as we can tell. Probably the main driver for this effect is one crucial difference in modeling impacts in the model *PAGE* as used for the *Stern Review* and *FUND*: *PAGE* puts more emphasis on the negative impacts of climate change, i.e., it will rarely produce a net global benefit from an increase in temperature for any time step.[9] *FUND* on the other hand has various sectors in which modest temperature increases in some regions can lead to net benefits, so that in particular in the earlier time periods impacts of climate change are positive for some regions.[10] Besides, *PAGE* includes an arbitrary catastrophe

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[8] Note that *PAGE* tends to report *lower* marginal impacts than *FUND* (Tol 2008).

[9] Note that *PAGE* does produce positive market impacts for some regions.

[10] Initially positive economic impacts of climate change are not unique to *FUND*, and are not a new finding. See Smith et al. (2001). For detailed discussions of *FUND's* estimated impacts and in particular their time profile as well as their regional distribution, see Tol (2002b) and Tol et al. (2003).

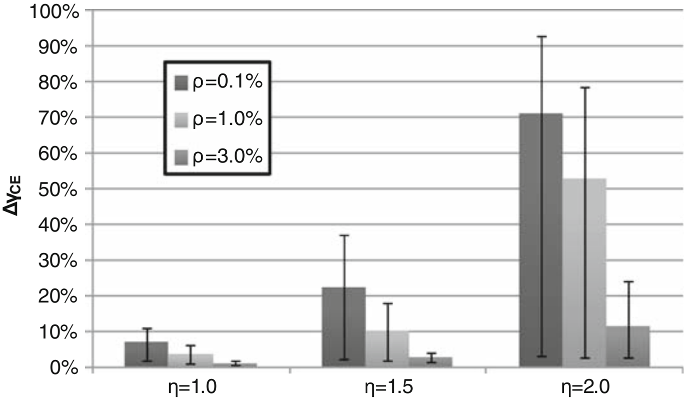

Fig. 2 Total damage with a regional welfare function

caused by climate change, while *FUND* only includes identified impacts—which does not imply that FUND cannot produce very large impacts (Tol 2003) or analyze supposedly catastrophic scenarios (Link and Tol 2004). Furthermore, *PAGE* assumes that vulnerability to climate change is constant, while *FUND* has that regions grow less vulnerable as they grow richer. Sterner and Perrsson (2008) and Tol and Yohe (2007b) show that this is an important assumption.

At the same time, our results mimic some key features of the *Stern Review* results: higher time preference rates and higher risk aversion always lead to lower impacts estimates. For time discounting, this is rather well established in the literature (e.g., Guo et al. 2006; Newell and Pizer 2003). That higher η values lead to lower damages is less straight forward, as it controls two effects at the same time. First, the effective discount rate is increased, which certainly leads to lower damage estimates. Second, more weight is given to unlikely but bad outcomes, i.e., the decision maker is assumed to be more risk averse, which should lead to higher damage estimates. Figure 1 shows that the first effect strongly dominates the second in the kind of uncertainty analysis employed for this paper, i.e., that the increase in the discount rate offsets the increase in risk aversion.

The *Stern Review* itself pointed out that a global welfare function cannot take into account how damages are distributed with respect to high/low income regions, and that a regional disaggregated welfare function would be a more appropriate choice. Figure 2 shows results using a social welfare function that is disaggregated into 16 world regions, again with the mean (and minimum and maximum) of the socio-economic scenarios for a costless mitigation policy.

There are three key insights: first, using a disaggregated regional social welfare function always increases total damage estimates; second, the role of η is reversed; and third, high η values lead to estimates that are very large.

We find higher damages for a regional disaggregated welfare function for all scenarios. A disaggregated regional welfare function in general gives higher weights to impacts in poor regions than in high income regions. In general (but not in every detail), *FUND* has more negative impacts in poor regions, so this result is not unexpected.

With a regional welfare function, η plays a third role, namely that of inequality aversion, in addition to the parameter of risk aversion and substitution of consumption over time. With this third role added, the response of the total damage estimates to higher values for η is

Table 1 Change in CBGE and CEBGE from a scenario without climate impacts to a mitigation policy scenario (to a business as usual scenario in brackets) for SRES scenario A2

	$\eta = 1.0$	$\eta = 1.5$	$\eta = 2.0$
Global welfare function (%)			
$\rho = 0.1$	1.33% (3.27%)	0.85% (2.40%)	0.40% (1.49%)
$\rho = 1.0$	0.40% (1.55%)	0.19% (0.92%)	0.08% (0.46%)
$\rho = 3.0$	0.01% (0.03%)	0.02% (−0.07%)	0.01% (-0.14%)
Regional welfare function (%)			
$\rho = 0.1$	4.27% (9.24%)	27.86% (32.60%)	91.07% (91.67%)
$\rho = 1.0$	1.52% (5.12%)	9.74% (13.95%)	70.58% (72.11%)
$\rho = 3.0$	0.08% (1.56%)	0.61% (3.29%)	10.25% (13.73%)

reversed, in particular the inequality and risk aversion aspect dominate the higher discount rate aspect of high η values and therefore total damage estimates increase with higher values for η. This directly points to one central problem with the kind of welfare function commonly employed in climate change analysis (and this paper), namely the over use of η to control three issues at the same time (cf. Beckerman and Hepburn 2007). A number of the critics of the *Stern Review* (e.g., Dasgupta 2007) have argued that while a low pure rate of time preference might be acceptable, one should pick a higher value for η, so that the overall discount rate is more in line with market interest rates. In the context of a global welfare function as used by Stern (2007) this suggestion makes sense, but with a regional welfare function the effect on the estimated damage may be unexpected.

Finally, we produce very large damage estimates for high η values with a regional welfare function. This is a direct manifestation of Weitzman (2009) fat tail argument: comparing the regional probabilistic results with deterministic runs, and a detailed analysis of the drivers of those extreme values shows that some regions approach very low consumption (subsistence) levels in some scenarios in our Monte Carlo analysis—and this implies that welfare in these regions, years and runs becomes large and negative, and potentially unboundedly so. With a global welfare function those extreme results in a few regions are averaged out, but with a regional welfare function these fat tails in single regions drive the analysis.

4.3 Mitigation Policy

While an analysis of the total expected damage of climate change is of interest, a more policy relevant question is what improvement a realistic policy that would have both mitigation costs and avoided damage benefits accounted for could achieve.

Table 1 compares the total damage of a scenario with no emission mitigation with the total damage of our mitigation policy scenario (in which case the total damage includes the now reduced impacts from climate change as well as the mitigation costs) for SRES scenario A2 for a probabilistic analysis. The A2 scenario is the scenario of choice in the *Stern Review*. For a global welfare function as used by the *Stern Review*, the best possible improvement is always significantly lower than the total damage estimate. Except for runs with high η values, this conclusion also holds for a regional welfare function. The runs with $\eta = 2$ have to be interpreted with care, since the manifestation of fat-tails showing up there might make the framework used to determine our policy response less appropriate.

Table 2 Carbon tax ($/tC in 1995 USD) in the year 2000 for SRES A2 scenario under a probabilistic analysis for the mitigation policy

	$\eta = 1.0$ (%)	$\eta = 1.5$ (%)	$\eta = 2.0$ (%)
Global welfare function(%)			
$\rho = 0.1$	40.63	23.75	11.88
$\rho = 1.0$	15.63	6.88	3.13
$\rho = 3.0$	0.63	0.63	0.63
Regional welfare function (%)			
$\rho = 0.1$	51.25	54.38	50.63
$\rho = 1.0$	21.25	25.63	31.25
$\rho = 3.0$	2.50	6.88	7.50

A global welfare function underestimates by a large margin the improvements that can be obtained by an actual mitigation policy. Table 2 compares the carbon tax levels in the year 2000 for the A2 scenario. Note the discrepancy in the results. While our total impact estimate is 3% for $\eta = 1$ and $\rho = 0.1\%$ compared to Stern's 5%, our social cost of carbon is $41/tC compared to Stern's $314/tC. This is probably explained by the highly non-linear impact function in the (adjusted) PAGE model. While the initial tax is higher for a regional welfare function, the change in the BGE for a regional welfare function is much larger for the mitigation policy than the change in the tax level. The prime reason for this is that the introduction of a regional welfare function not only gives more weight to damages in low income regions, but also mitigation costs in poor regions also get a higher weight, thereby balancing the effect of the regional welfare function somewhat.

Table 3 highlights the importance of distributional issues and uncertainty in climate change. Table 3 shows our estimate of the total impacts of climate change using a global welfare function ignoring uncertainty and compares this to the regional welfare function. In the global welfare function, global average impacts are computed before being converted to utility. In the regional welfare function, regional average impacts are converted to utility and then averaged for the world. Irrespective of the rates of pure time preference or risk aversion, the regional welfare function implies impacts that are substantially higher. This is well-known in the literature (Azar and Sterner 1996; Fankhauser et al. 1997; Azar 1999; Anthoff et al. 2009). It appears that the *Stern Review* overlooked this. With uncertainty, the difference between a global and a regional welfare function is even stronger.

Qualitatively, the results for the A2 scenario hold for the other scenarios as well. Quantitatively, the results are different, of course, and where the relationship is ambiguous (e.g., between η and $\Delta\gamma$), different scenarios may show different signs. Table 4 shows the total impact of climate change for five alternative socio-economic and emissions scenarios. The A2 scenario is generally in the middle of the range. Hotter (FUND) and poorer (B2) scenarios show higher impacts, while cooler (B1) and richer (A1b) scenarios show lower impacts.

5 Conclusion

This paper defines various balanced growth equivalences, and applies them to compute the impacts of climate change and the benefits of emission reduction with the integrated assessment model *FUND*. We conduct a wider sensitivity analysis than run by the *Stern Review*.

Table 3 Change in BGE and EBGE for total damage estimates for a business as usual scenario for SRES scenario A2 without uncertainty

	$\eta = 1.0$ (%)	$\eta = 1.5$ (%)	$\eta = 2.0$ (%)
Global welfare function (%)			
$\rho = 0.1$	1.53	0.59	−0.15
$\rho = 1.0$	0.07	−0.46	−0.76
$\rho = 3.0$	−0.92	−0.95	−0.95
Regional welfare function (%)			
$\rho = 0.1$	3.05	2.67	2.48
$\rho = 1.0$	1.06	1.20	1.72
$\rho = 3.0$	−0.51	0.40	1.42

Table 4 Total damages for probabilistic runs by socio economic scenario

	$\eta = 1.0$ (%)			$\eta = 1.5$ (%)			$\eta = 2.0$ (%)		
	$\rho = 0.1\%$	$\rho = 1.0\%$	$\rho = 3.0\%$	$\rho = 0.1\%$	$\rho = 1.0\%$	$\rho = 3.0\%$	$\rho = 0.1\%$	$\rho = 1.0\%$	$\rho = 3.0\%$
Global welfare function									
FUND	4.50	2.25	0.23	3.45	1.45	0.06	2.24	0.80	−0.05
A1b	1.49	0.49	−0.20	0.56	0.02	−0.28	−0.01	−0.21	−0.32
A2	3.27	1.55	0.03	2.40	0.92	−0.07	1.49	0.46	−0.14
B1	0.09	−0.16	−0.32	−0.13	−0.26	−0.33	−0.25	−0.30	−0.33
B2	3.42	1.57	−0.01	2.59	0.97	−0.11	1.66	0.49	−0.19
Regional welfare function									
FUND	11.30	6.45	1.89	37.26	18.28	4.14	92.74	78.66	24.20
A1b	4.83	2.54	0.94	14.87	5.38	1.97	80.28	44.69	5.72
A2	9.24	5.12	1.56	32.60	13.95	3.29	91.67	72.11	13.73
B1	1.92	1.22	0.70	2.39	1.98	1.77	3.42	3.04	2.99
B2	8.35	4.46	1.40	25.60	11.02	3.03	88.74	65.82	12.00

We find that the impacts of climate change are sensitive to the pure rate of time preference, the rate of risk aversion, the level of spatial disaggregation, the inclusion of uncertainty, and the socio-economic scenario. Our results span a wider range in both directions compared to the *Stern Review*, thereby questioning the assertion that the high results obtained by the *Stern Review* are robust. We find that the guess of the *Stern Review* that a regional welfare function might increase overall damage estimates by a quarter (Stern 2007, p. 187) is very conservative. In our runs, the introduction of a regional welfare function, in particular in combination with a high risk aversion, has a much larger effect on the results. Finally, we show that the *Stern Review* was wrong to equate the impact of climate change and the benefits of emission reduction—their "optimal" climate policy does not maximize welfare in the mathematical sense of the word. Qualitatively, this was known. Quantitatively, we show that this is a big mistake.

The results also show areas that need more research work. This includes improved socio-economic and climate scenarios, and better and more complete estimates of the impacts of climate change. In particular, disentangling intertemporal substitution from risk aversion and inequality aversion is a high priority (e.g., Carlsson et al. 2005). With only one parameter to control three important effects, as commonly used in climate policy analysis, model- and scenario-specific ambiguities emerge. The fat tails that showed up in some of our results with high risk aversion and a regional welfare function are another area for further research.

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