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Climate Policy Under Uncertain and Heterogeneous Climate Damages

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Abstract We highlight that uncertainty about climate damages and the fact that damages will be distributed heterogeneously across the global population can jointly be an argument for substantially stricter climate policy even if uncertainty and heterogeneity in isolation are not. The reason is that a given climate risk borne by fewer people implies greater welfare losses. However, these losses turn out to be significant only if society is both risk and inequality averse and if climate damages are highly heterogeneous. We discuss how insurance and self-insurance of climate risk could theoretically mitigate this joint effect of uncertainty and heterogeneity and thus admit weaker climate policy. Insurance provides more efficient risk sharing and self-insurance allows strongly impacted individuals to compensate damages by increasing savings. We first use a simple analytical model to introduce the different concepts and then provide more realistic results from the integrated assessment model DICE.

Keywords Climate change · Climate policy · Stabilization target · Uncertainty · Heterogeneity · Damages · Insurance

1 Introduction

Climate change is surrounded by great uncertainty. However, a number of integrated assessment studies have found that uncertainty has only a minor effect on first-best climate policy and emissions (Peck and Teisberg 1993; Nordhaus 1994; Nordhaus and Popp 1997; Ulph and Ulph 1997; Webster 2002). An exception is Weitzman (2009), who shows that uncertainty

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matters if it is fat-tailed (see also Weitzman 2010; Nordhaus 2009, for a discussion). All these studies are based on the assumption of a representative agent. The real society with heterogeneous preferences, income levels, and climate damages is replaced by a fictitious homogeneous one that is supposed to lead to the same equilibrium prices and savings. A representative agent is known to exist for complete market economies (Constantinides 1982), which in this context would include complete insurance markets for climate damages. However, markets are far from complete, and risks are not shared efficiently. As an example, currently only about 20 % of catastrophic damages are insured (Mills 2005).

Introducing explicit damage heterogeneity, or any heterogeneity for that matter, immediately raises questions of equity that where conveniently omitted in representative agent models. How should impacts imposed on different people be valued and aggregated? Global impact studies are still rare and mostly just add up the economic damages and willingness-to-pay for avoiding non-economic damages of all individuals (Cline 1992; Nordhaus 1994; Fankhauser 1994; Nordhaus 2006; Hope 2006; an exception is Tol (2002). Poor people have less to lose in dollar terms and generally have a lower willingness-to-pay for avoiding non-economic damages, but they suffer greater utility losses for every dollar lost. Just adding damages in dollar terms thus amounts to valuing the utility losses of poor people lower than of rich people (see Fankhauser et al. 1997). We will, in contrast, reconstruct the heterogeneous damages from the aggregate estimates above and then, following Fankhauser et al. (1997), explicitly use a social welfare function to aggregate to the overall population. In the welfare function we separate risk aversion from inequality aversion in order to clarify the interaction between the two.

There are several papers that analyze regional damage heterogeneity without uncertainty (Nordhaus and Yang 1996; Azar 1999; Fankhauser and Tol 2005; Anthoff et al. 2009; Anthoff and Tol 2010). This paper is closest to Tol (2003) and Anthoff and Tol (2009), who take uncertainty into account. Using the integrated assessment model FUND they show that damage- and income heterogeneity in combination with uncertainty can have a big effect on the benefits of emission reductions and even lead to a break-down of cost-benefit analysis if the uncertainty is fat-tailed in some regions. Using a simple analytical model, our paper intends to clarify and separate the effects of heterogeneity and uncertainty. It also shows how insurance markets and self-insurance can mitigate them. Numerical results for the benefits of various concentration targets are then obtained with the integrated assessment model DICE.

More specifically, the five main points of this article are the following: (i) Uncertainty and damage heterogeneity can jointly have a strong effect on optimal climate policy even if their separate effects are negligible. The reason is that the same risk borne by fewer people implies greater welfare losses. The fact that uncertainty has only a small effect in other studies is hence at least partly due to their assumption of a representative agent and, more specifically, the implicit assumption of efficient risk sharing. (ii) Under constant relative risk aversion and inequality aversion, income inequality favors stricter climate policy only if people with low income either suffer higher relative damages or bear lower relative abatement costs than people with high income. (iii) The introduction of complete insurance markets essentially lowers the aggregate risk premium associated with heterogeneous damages to the one for homogeneous damages of the same amount. Complete insurance would therefore allow a significant relaxation of climate policy. (iv) Even in the absence of insurance markets, individuals can still mitigate the effect of damage heterogeneity substantially by self-insuring, i.e. increasing savings. This is particularly effective under lax climate policy, because it allows to shift consumption from the short term, where abatement costs are low, to the long term, where damages are high. (v) For all results we shortly discuss their dependence on the available information about aggregate climate damages and the distribution of damages across the population. As known in the literature, better information decreases the effectiveness of insurance markets in the absence of market failures but increases the effectiveness of self-insurance.

The article is structured as follows. In Sect. 2 we introduce the different concepts in an analytical model, where we can derive closed-form solutions. After a short introduction of the model assumptions, we discuss three settings: In Sect. 2.1 neither insurance with others nor self-insurance is possible. In Sect. 2.2, a perfect insurance market is available. In Sect. 2.3 self-insurance is possible whereas insurance with others is not. Section 3 then shows numerical results from the integrated assessment model DICE. Parallel to Sect. 2, Sects. 3.1, 3.2, and 3.3 discuss the three different settings. Finally, Sect. 4 concludes.

2 Analytical Model

In this section, we use a simple analytical model and convenient functional forms to define and discuss the effects of uncertainty and damage heterogeneity on welfare.

We make the following assumptions: (i) All agents have a constant absolute risk aversion utility function, $u(c) = -e^{-Ac}/A$, with the same degree of absolute risk aversion A. (ii) Aggregate, additive climate damages are normally distributed: $D \sim \mathcal{N}(\mu, \sigma)$. (iii) The heterogeneity of damages can be described by only two cohorts: one cohort is affected by climate damages, the other one is not. The affected cohort constitutes a share k of the population. Thus, if average per capita damages equal D for the overall population, per capita damages are $D^{(1)} = D/k$ for the affected and $D^{(2)} = 0$ for the unaffected, where the superscripts indicate the cohort[1]. The homogeneous case is obtained for $k = 1$.

All three assumptions will be replaced by more realistic ones in the numerical model in Sect. 3. Furthermore, we assume that the climate risk is the only risk in the economy, i.e. there is no systemic macroeconomic or idiosyncratic income risk. For most of this section we neglect inequality in gross income before damages in order to isolate the effect of damage heterogeneity, but we consider income inequality at the end of Sect. 2.1.

2.1 No Insurance

In this subsection, we assume the cohort that is exposed to the climate risk cannot insure with the rest of the population. This is not a completely unrealistic assumption. As mentioned in the introduction, currently only about 20 % of catastrophic risks are insured (Mills 2005), and big part of climate impacts will be in the form of catastrophes such as floods, heat waves, storms and so on. Gollier (2005) gives an overview of possible reasons for the difficulties of insuring catastrophic risks.

The certainty equivalent (CE) consumption of an affected individual, $\bar{c}^{(1)}$, where the over-bar refers to the CE and the superscript indicates the cohort, is implicitly defined over

$$E\left[u\left(y - D/k\right)\right] = u\left(\bar{c}^{(1)}\right), \tag{1}$$

where y is gross consumption before damages. For simplicity we do not explicitly specify the dependence of $\bar{c}^{(1)}$ on $u,\ y,\ D$, and k. Under the functional assumption at the beginning

[1] As noted by one of the reviewers, there is a lower limit on k depending on D and gross consumption y of the affected cohort, because individual damages can not exceed gross consumption: $y - D/k > 0$, or $k > D/y$. Allocating the same damages on an even smaller fraction of the population would only be possible, if this fraction had higher than average gross consumption.

of this section, we get

$$\bar{c}^{(1)} = y - \frac{\mu}{k} - \frac{A}{2}\frac{\sigma^2}{k^2}. \tag{2}$$

The risk premium is then given by $\pi^{(1)} = E[c^{(1)} = y - D/k] - \bar{c}^{(1)} = (A/2)\,\sigma^2/k^2$.

For the aggregation to the overall population, we use a social welfare function. In order to separate the effect of risk / risk aversion from the effect of inequality / inequality aversion on welfare, we assume it to be of the following form, which will be explained below,

$$\begin{aligned} W(c^{(1)}, c^{(2)}, k) &= k\, v\left(u^{-1}\left(E\left[u(c^{(1)})\right]\right)\right) + (1-k)\, v\left(u^{-1}\left(E\left[u(c^{(2)})\right]\right)\right) \\ &= k\, v(\bar{c}^{(1)}) + (1-k)\, v(c), \end{aligned} \tag{3}$$

Here, $u^{-1}(\cdot)$ is the inverse of the utility function, and $v(\cdot)$ is an increasing function expressing inequality aversion. In the second step we used the fact that the second cohort does not suffer damages. Thus, we take the function v of the certainty equivalent consumption levels of the individuals and then sum over the individuals. Society is risk averse, if it is worse off with uncertain consumption than with consumption fixed at its expected values, $W(c^{(1)}, c^{(2)}, k) < W(E[c^{(1)}], E[c^{(2)}], k)$. Since v is an increasing function, this translates to $\bar{c}^{(i)} < E[c^{(i)}]$, which in turn implies strict concavity of u, $E[u(c^{(i)})] < u(E[c^{(i)}])$. Society is risk-neutral, if the inequalities are replaced by equalities so that u has to be linear. Thus, risk aversion is determined by the curvature of u. Society is inequality averse, if it is worse off with a heterogeneous distribution of certain consumption over individuals than with a homogeneous distribution, where all individuals enjoy average consumption, $W(\bar{c}^{(1)}, \bar{c}^{(2)}, k) < W(k\bar{c}^{(1)} + (1-k)\bar{c}^{(2)}, k\bar{c}^{(1)} + (1-k)\bar{c}^{(2)}, k)$. This implies strict concavity of v, $kv(\bar{c}^{(1)}) + (1-k)v(\bar{c}^{(2)}) < v(k\bar{c}^{(1)} + (1-k)\bar{c}^{(2)})$. Society is inequality-neutral, if the inequalities are replaced by equalities so that v has to be linear. Thus inequality aversion is determined by the curvature of v. This way of separating inequality aversion from risk aversion is analogous to the way (Kreps and Porteus 1978) separate the elasticity of inter-temporal substitution from risk aversion.

As customary, we define the certainty and equity equivalent (C&EQE) consumption level as the certain and homogeneous (across the population) consumption level that gives the same welfare as an uncertain heterogeneous one (e.g. Anthoff and Tol 2009). We denote it by $\hat{\bar{c}}$, where the bar still refers to the CE and the hat refers to the EQE. More formally, we define

$$W(c^{(1)}, c^{(2)}, k) = v\left(\hat{\bar{c}}(u, v)\right) \tag{4}$$

where we omit the dependence of $\hat{\bar{c}}$ on $c^{(1)}$, $c^{(2)}$, and k. We consider four special cases:

(i) Society is both risk- and inequality averse. More specifically, we assume $v \equiv u$ and get the utilitarian welfare function $W(c^{(1)}, c^{(2)}, k) = k\, E[u(c^{(1)})] + (1-k)E[u(c^{(2)})]$. Somewhat sloppily we will denote $\hat{\bar{c}}(u, u)$ shortly by $\hat{\bar{c}}$. Under the functional assumptions of this section we get

$$\hat{\bar{c}} = y - \ln\left(1 - k\left(1 - e^{A\left(\mu/k + (A/2)\sigma^2/k^2\right)}\right)\right)/A. \tag{5}$$

(ii) Society is only risk averse. For a linear $v(c) = c$, we simply add the certainty equivalents of all individuals, $W(c^{(1)}, c^{(2)}, k) = k\,\bar{c}^{(1)} + (1-k)\bar{c}^{(2)}$. We call the resulting consumption the CE consumption of the population and denote it by $\bar{c} = \hat{\bar{c}}(u, v(c) = c)$.

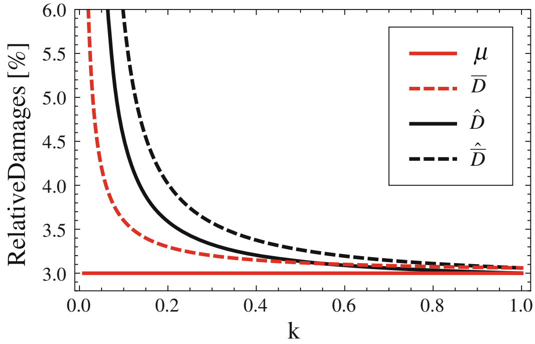


Fig. 1 Expected (μ), CE ($\bar{D}$), EQE ($\hat{D}$), and C&EQE ($\hat{\bar{D}}$) damages in relative terms of per capita income of $y = \$7{,}000$/year and as a function of k. The parameter values are $A = 3/7$, $\mu/y = 3\,\%$, $\sigma/y = 2\,\%$. Color code: *Red lines* refer to results without inequality aversion, *black lines* to results for a utilitarian. *Solid lines* refer to results without risk aversion, *dashed lines* to results with risk aversion. (Color figure online)

Under the functional assumptions of this section we get

$$\bar{c} = k\bar{c}^{(1)} + (1-k)y = y - \mu - \frac{A}{2}\frac{\sigma^2}{k}. \tag{6}$$

Holding average damages D fixed: The smaller k, the greater is the risk of the affected individuals, namely D/k. This leads to an increase proportional to $1/k^2$ of the risk premium of the affected (Eq. 2) and hence an increase proportional to $1/k$ of the risk premium of the overall population (Eq. 6). Hence, the risk premium increases five times, for instance, if only 20 % of the population are affected by climate damages. It is straightforward to verify that $\bar{c} \geq \hat{\bar{c}}$, i.e. inequality aversion decreases C&EQE consumption.

(iii) Society is only inequality averse. For a linear $u(c) = c$ we get $W(c^{(1)}, c^{(2)}, k) = k\, v(E[c^{(1)}]) + (1-k)\, v(E[c^{(2)}])$. We call the resulting C&EQE consumption the EQE consumption of the population and denote it by $\hat{c} = \hat{\bar{c}}(u(c) = c, v)$. Under the functional assumptions of this section and assuming $v(c) = -e^{-Ac}/A$ we get

$$\hat{c} = y - \ln\left(1 - k\left(1 - e^{A\mu/k}\right)\right)/A. \tag{7}$$

(iv) Society is neither risk nor inequality averse. For both linear $u(c) = c$ and $v(c) = c$ we get $W(c^{(1)}, c^{(2)}, k) = k\, E[c^{(1)}] + (1-k)\, E[c^{(2)}]$ and welfare is given by expected average consumption. For the example of this section, we have $W(c^{(1)}, c^{(2)}, k) = y - \mu$.

Figure 1 shows exemplary results for expected, CE, EQE, and C&EQE damages, which are defined as the difference in the corresponding values for consumption with and without damages, i.e. $\hat{\bar{D}} = \hat{\bar{c}}_{\mu=0;\sigma=0} - \hat{\bar{c}}$, for instance. It shows that uncertainty has a substantial effect on damages both with and without inequality aversion if k is small.

What happens if gross consumption, i.e. consumption before damages, differs between the cohorts? There are two effects (i) If absolute risk aversion A depends on the consumption level and more specifically decreases in consumption, then the risk premium will increase if the affected cohort is poorer than average. Under the assumption of constant absolute risk aversion in this section, though, this effect is absent. It will be present in the numerical model in Sect. 3. (ii) Gross consumption inequality has an effect on net consumption inequality and hence EQE consumption. Net inequality is decreased by gross inequality compared to the case of equal gross consumption, if the affected are richer than the non-affected by an amount smaller than twice $\bar{D}^{(1)}$. The initial wealth then partly compensates for damages. Inequality is increased otherwise. Smaller net consumption inequality leads to an increase in EQE consumption, or equivalently a decrease in EQE damages.

2.2 Perfect Insurance Market

In the last section, the affected individuals didn't have the possibility to insure with the rest of the population. Heterogeneity then leads to a substantial increase in C&EQE damages. Now we investigate to what extent a complete contingent claims, or insurance, market can mitigate this result. Since we assume no other risks in the economy, the benefits from such a market are due to risk sharing not diversification.

For each state of the world, characterized by average damages D, we introduce a tradable contingent claim that pays off average damages in the corresponding state of the world. We denote the prices of these claims by p_D, and the amounts of claims purchased by the affected and unaffected by $x_D^{(1)}$ and $x_D^{(2)}$, respectively. The equilibrium conditions for the affected and unaffected are

$$\begin{aligned} &\max_{x_{1,D}} \left\{ E\left[u\left(y - D/k + x_D^{(1)} D - \int_{-\infty}^{\infty} x_{D'}^{(1)} p_{D'} dD' \right) \right] \right\}, \\ &\max_{x_{2,D}} \left\{ E\left[u\left(y + x_D^{(2)} D - \int_{-\infty}^{\infty} x_{D'}^{(2)} p_{D'} dD' \right) \right] \right\}, \\ &\text{s.t. } \forall D: \; k\, x_D^{(1)} + (1-k) x_D^{(2)} = 0. \end{aligned} \tag{8}$$

The integrals $\int_{-\infty}^{\infty} x_{D'}^{(i)} p_{D'} dD'$ equal the overall amount spent on the contingent claims portfolio, and the $x_D^{(i)} D$ equal the random payoffs of the portfolio. The last equality in Eq. (8) is the market clearing condition, which has to hold in every state of the world.

In the following we verify that under the assumptions of this section, individuals purchasing the same amount of per capita damages in all states of the world, i.e. $x_D^{(i)} = x^{(i)}, \; i = 1, 2$, is an equilibrium. Hence, in our simple setting, it is not necessary to have separate contingent claims for all states of the world to obtain the complete market equilibrium, but it is sufficient to have a single claim that pays off average per capita damages however high they turn out to be. This is a consequence of the linearity of individual damages in average damages in our simple formulation of heterogeneity. It won't hold for the formulation of heterogeneity used in the numerical model in Sect. 3.2. Substituting $x_D^{(i)} = x^{(i)}, \; i = 1, 2$ into Eq. (8) and denoting $p = \int_{-\infty}^{\infty} p_{D'} dD'$, we get

$$\begin{aligned} &\max_{x_1} \left\{ E\left[u\left(y - D/k + x^{(1)}(D - p) \right) \right] \right\}, \\ &\max_{x_2} \left\{ E\left[u\left(y + x^{(2)}(D - p) \right) \right] \right\}, \\ &\text{s.t. } k\, x^{(1)} + (1-k) x^{(2)} = 0. \end{aligned} \tag{9}$$

These conditions are solved under the functional assumptions of this section by

$$p = \mu + A\,\sigma^2, \tag{10}$$

$$x^{(2)} = -1 = -\frac{k}{1-k} x^{(1)}. \tag{11}$$

In the equilibrium described by Eqs. (10) and (11), every individual suffers per capita damages, the risk is equally distributed between all individuals. This result is due to the assumption of constant absolute risk aversion. For decreasing absolute risk aversion, the affected would carry a smaller risk in equilibrium because the insurance premium they have to pay makes

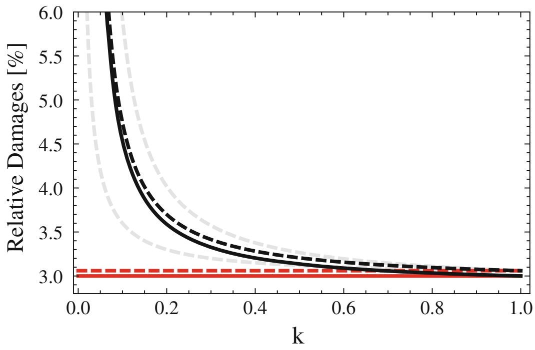


Fig. 2 The same as in Fig. 1, in the same color code, but for the market solution. Damages without insurance are shown in *light gray*. (Color figure online)

them poorer and hence more risk averse. This will be the case, albeit weakly, in Sect. 3.2. The price of per capita damages in Eq. (10) equals the marginal certainty equivalent damages if the individual already suffers per capita damages, $p = d/dx\,(x\mu + A/2\,x^2\sigma^2)|_{x=1}$. Like the allocation of per capita damages, it does not depend on k.

For the CE and C&EQE consumption, we get

$$\bar{c} = y - \mu - \frac{A}{2}\sigma^2, \tag{12}$$

$$\hat{\bar{c}} = y + \frac{A}{2}\sigma^2 - \ln\left(1 - k\left(1 - e^{A\left(\mu + A\sigma^2\right)/k}\right)\right)/A \tag{13}$$

The corresponding damages are shown in Fig. 2. Due to the efficient risk sharing, the risk premium in the market allocation is reduced to the premium for the homogeneous case, i.e. Eq. (6) for $k = 1$. The EQE is not affected by an insurance market. If individuals are risk-neutral there is no reason for buying insurance.

The market equilibrium crucially depends on the information structure. The main dimensions are: (i) whether it is known how many individuals are affected and who they are, (ii) the probability distribution on aggregate damages, and (iii) whether all this information is public or private.

(i) If nobody knows whether she is affected and all individuals have the same probability of being affected, then individuals are homogeneous ex ante. A perfect insurance market then leads to a homogeneous distribution of consumption net of damages ex post, as well. This homogeneity is obtained via contracts that transfer consumption ex post, i.e. once damages have been realized, from the unaffected to the affected. This leads to an increase of the EQE compared to the case where it is known who is affected. Thus, less information about who is affected increases EQE consumption. This is an instance of the well-known Hirshleifer effect (Hirshleifer 1971), which might be summarized as "realized risks cannot be insured and shared".

(ii) The same effect applies to information about the value of aggregate climate damages. Once damages are known, there is no way to share damage risk. Since it can be expected that uncertainty will be resolved over time, insurance contracts will either have to be made soon, which, of course, brings problems of its own, or insurance will loose some of its effectiveness.

(iii) If the information is asymmetric, i.e. if, for instance, the affected know that they are affected but others don't, or if hidden actions influence damages, the classical problems of adverse selection and moral hazard would also hamper insurance markets and bring the resulting allocation closer to the one in Sect. 2.1.

2.3 Self-Insurance

Even if insurance contracts are not available, affected individuals can use savings, or self-insurance, to mitigate utility losses. We assume there are two periods, where the first period covers t_1 years. Damages occur only in the second period. Self-insurance is done by increasing savings in the first period and thereby shifting consumption to the second period. We can decompose damages into expected damages and a zero-mean risk, $D = \mu + D_0$ and then distinguish a deterministic and a stochastic reason for increasing savings, namely (i) consumption smoothing and (ii) precautionary savings (see e.g. Gollier 2004). (i) Expected damages decrease the second period consumption level. This increases marginal utility and hence the propensity to save in the first period. (ii) If the decision maker is prudent, i.e. if she has convex marginal utility, then the zero mean risk increases marginal utility and hence savings (Jensen's inequality).

More formally, we denote the interest rate by r and the pure rate of time preference by β. The endowments in the two periods for both cohorts are denoted by c_1 and c_2, respectively, where the subscripts denote the time period not the cohort. We assume individuals maximize the sum of discounted utility over time. Thus the affected and unaffected cohorts solve the independent maximization problems

$$\max_{s^{(1)}} \left\{ u(y_1 - s^{(1)}) + e^{-\beta t_1} E\left[u\left(y_2 + s^{(1)} e^{r t_1} - D/k \right) \right] \right\}$$
$$\max_{s^{(2)}} \left\{ u(y_1 - s^{(2)}) + e^{-\beta t_1} u\left(y_2 + s^{(2)} e^{r t_1} \right) \right\}.$$

For the functional forms assumed in this section we get

$$s^{(1)*} = \left(1 + e^{r t_1}\right)^{-1} \left(y_1 - y_2 + \frac{t_1(r-\beta)}{A} + \frac{\mu}{k} + \frac{A}{2}\frac{\sigma^2}{k^2} \right),$$
$$s^{(2)*} = \left(1 + e^{r t_1}\right)^{-1} \left(y_1 - y_2 + \frac{t_1(r-\beta)}{A} \right), \tag{14}$$

The last two terms in the second factor of $s^{(1)*}$ equal the certainty equivalent damages of the affected and describe additional savings due to damages. The former of them is due to consumption smoothing, the latter is due to prudence. Savings are increasings in the interest rate (and the first period length) if it is low, but decreasing if it is high. The reason for the latter is that a higher interest rate provides higher consumption in the second period, which decreases the incentive to save.

In order to isolate the additional savings due to heterogeneity, we can choose the interest rate r such that individuals have no incentive to save in the homogeneous case ($k = 1$), i.e. $u'(y_1) = e^{(r-\beta)t_1} E[u'(y_2 - D)] \rightarrow s^{(1)*}|_{k=1} = 0$. Under the functional forms of this section, we get $r = \beta + (A/t)(y_2 - \mu - (A/2)\sigma^2 - y_1)$. Substituting this into Eq. (14) leads to rather lengthy and little intuitive expressions. A numerical example is therefore shown in Fig. 3. The affected save substantially more, whereas the unaffected save less than in the homogeneous case. The latter is because the unaffected enjoy greater consumption in the second period than in the homogeneous case and hence shift consumption to the first period. The additional savings of the affected are mainly due to consumption smoothing (solid lines in Fig. 3). The aggregate additional savings are small down to about $k = 0.05$, which would justify the assumption of a fixed interest rate even in the presence of non-constant returns.

In order to measure the impact of self-insurance on welfare, we have to accommodate the temporal dimension. Therefore we generalize the certainty equivalent to a certainty and

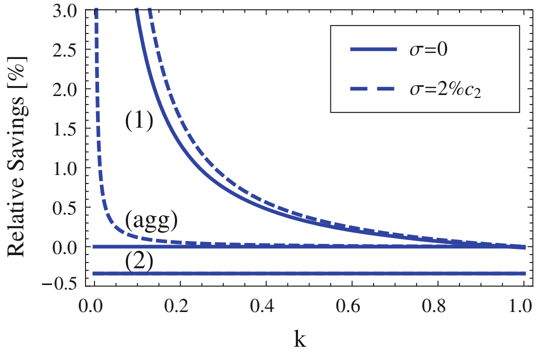


Fig. 3 Additional savings relative to consumption as a function of the infliction rate k. Savings for affected, unaffected, and aggregate savings are denoted by (1), (2), and (agg), respectively. The first period covers $t_1 = 50$ years, it is $\beta = 0.1\,\%$, $y_1 = \$7{,}000$ and $y_2 = \$21{,}000$/Cap/year. The other parameter values are as in Fig. 1

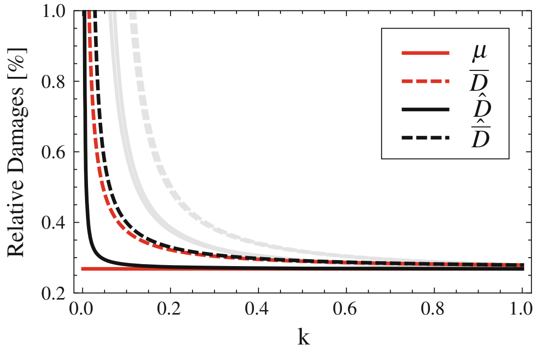


Fig. 4 The same as in Fig. 1 in the same color code but for the two-period model with self-insurance. Parameter values are as in Fig. 3. Damages without self-insurance are shown in *light gray*. (Color figure online)

zero-growth equivalent (C&ZGE) consumption $\tilde{\bar{c}}^{(1)}$, where the tilde refers the ZGE and the bar to the CE. For the affected without self-insurance, for instance, it is implicitly defined over

$$u(y_1) + e^{-\beta t_1} E\left[u\left(y_2 - D/k\right)\right] = u\left(\tilde{\bar{c}}^{(1)}\right)\left(1 + e^{-\beta t_1}\right), \tag{15}$$

An arbitrary consumption vector $(c_1,\ c_2)$ is replaced by a constant one $(\tilde{\bar{c}}^{(1)},\ \tilde{\bar{c}}^{(1)})$ that yields the same utility. For the more general concept of balanced growth equivalents, where consumption grows at a constant rate instead of being constant, see Mirrlees and Stern (1972) and Anthoff and Tol (2009). Parallel to Eq. (3), the welfare function is defined as the following sum over the two cohorts:

$$W(k) = k\, g\left(\tilde{\bar{c}}^{(1)}\right) + (1-k)\, g\left(\tilde{\bar{c}}^{(2)}\right),$$

and the C&ZG&EQE $\hat{\tilde{\bar{c}}}$ is then defined analogous to Eq. (4). Its explicit form under the functional assumptions of this section is lengthy, so that we show a numerical example in Fig. 4 instead. It shows that self-insurance substantially reduces C&ZG&EQE damages for low k. The fact that damages without risk and inequality aversion are not independent of k if self-insurance is not available (lower solid gray line) is due to the finite elasticity of intertemporal substitution. Comparing Fig. 4 to Fig. 2 shows that self-insurance mainly lowers welfare losses due to inequality, whereas insurance mainly lowers the risk premium.

In the last section we highlighted that the equilibrium in an insurance market crucially depends on the information available about who is affected and about the value of aggregate damages, and that utilitarian social welfare is larger the greater the uncertainty. In contrast, self-insurance is hampered by uncertainty. Only having a certain probability of being affected, for instance, lower savings to a level, which is ex post inefficient if the individual is actually affected. As it should be expected in a situation where individuals are independent of each other, information enhances the welfare gains from self-insurance.

3 Numerical Model

We now use the integrated assessment model DICE (Nordhaus 2008) to obtain more realistic results. DICE is a Ramsey-type growth model coupled to a simple climate box model that translates greenhouse gas emissions resulting from economic production to concentration, radiative forcing, atmospheric and oceanic warming and finally economic impacts. In addition to the investment into the aggregate capital stock, there is a second decision variable called the emissions control rate, which reduces emissions at given abatement costs.

We replace the assumptions of the analytical model in the last section by the following more realistic ones: (i) All agents are described by a constant relative risk aversion utility functions, $u(c) = (c^{1-\gamma} - 1)/(1-\gamma)$, with the same relative risk aversion $\gamma = 3$. In contrast to Nordhaus, who uses a pure rate of time preferences that declines from $\beta = 1.5\,\%$/year to zero over time, we choose a constant $\beta = 0.1\,\%$/year (see Dasgupta 2008, for a justification).

(ii) We use $\mathcal{L}og - \mathcal{N}(ln(2.6), 0.33)$ (Wigley and Raper 2001) as probability density function (PDF) on climate sensitivity. In the DICE function for aggregate relative damages as a function of global mean temperature $d(T) = aT^b/(1 + aT^b)$ we use the joint PDF on a and b derived from an expert elicitation by Roughgarden and Schneider (1999). Figure 5 shows exemplary distributions. In the following we use an equiprobable descriptive sampling with 10×10 sample points to represent the uncertainty.

(iii) Estimates of the geographic distribution of climate damages are only available on a world regional or at best on a country scale. The damage heterogeneity in the model RICE

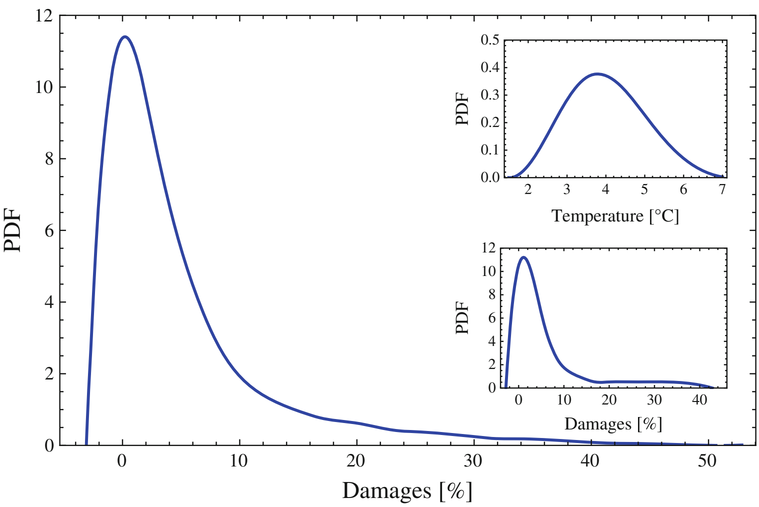


Fig. 5 Climate damage PDF in 2100 for a 1,000 ppmv concentration target. The *inset upper graph* shows the warming for the same year and scenario, and the lower one shows the damage distribution for the fixed average warming in this year of $T = 4.04\,°C$

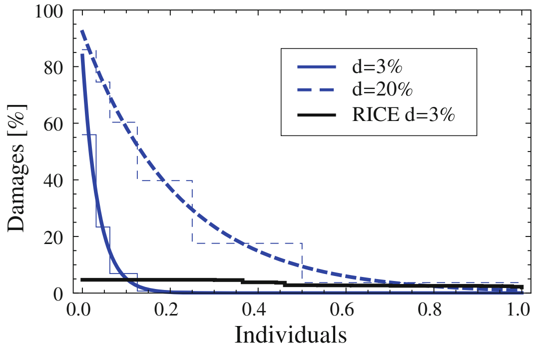


Fig. 6 Distribution of relative damages over individuals for two different values of aggregate damages indicated in the plot legend. The value of the heterogeneity parameter is $\eta = 0.05$. The step functions are the discritizations used in the numerical model. Also shown is the damage distribution in the RICE model (Nordhaus 2010)

(Nordhaus and Yang 1996) is included in Fig. 6. These estimates neglect the intra-regional heterogeneity. To our knowledge there are no studies on the global distribution of climate damages with a finer resolution than the country level. We will argue that most of the heterogeneity of climate damages will be below the country level. We will do so by ways of simple examples, and more research is called for at this point.

We shortly consider two broad examples, ecosystem services and extreme events. Ecosystem services constitute only a minor share of aggregate national GDP (6–17 %), but for the poorer part of the population ecosystem services like collecting fire wood, or fishing and farming can easily determine up to 90 % of their income (TEEB 2010). Ecosystem services will be severely impacted by climate change. A mass extinction of fish species due to ocean acidification in the second half of the century (Brakkes et al. 2008), for instance, is conceivable. This would strongly impact subsidence fishers while it would only have a minor effect on countries' GDP.

Lacking detailed studies on the damage distribution of extreme events and potential shifts in their rate of occurrence, we use some rough estimates to support our intuition about the strong sub-national heterogeneity of impacts from extreme events. Three major extreme events with well recorded damages for which a connection to climate change is discussed are Hurricane Katrina (Kwasinski and Weaver 2005; IPCC 2011), the European heat wave in 2003 (Zaitchik et al. 2006; Stott et al. 2004), and the Russian heat wave and the resulting forest fires in 2010 (Barriopedro et al. 2011; Otto et al. 2012). Table 1 gives the number of people that have been affected by damages of different severeness as well as an estimate of overall direct monetary losses. Only a very small fraction of the population suffered high damages or death. Climate damages from an increased frequency or severity of extreme events therefore have to be modeled as highly heterogeneous on a sub-country scale.

The preceding examples are only indicative and more research is needed before a heterogeneous damage function can be calibrated. Therefore, we use a conceptual parametrization of heterogeneity and perform sensitivity analyses. In contrast to the simple parametrization in the analytical model in Sect. 2, increasing aggregate damages lead to both higher damages for the affected and a greater share of affected individuals. To take this into account, we use the following parametrization: We index individuals by $i \in [0, 1]$ and assume individual damages are described by $\delta(i) = d^{\eta} e^{-b\,i}$, where d are average damages, η is a free parameter for the degree of heterogeneity, which now replaces the k of Sect. 2, and b is chosen such that the average damages actually equal d, $\int_0^1 \delta(i)di = d$. The homogeneous distribution is obtained for $\eta = 1$. The distribution of damages over individuals for a fixed value of

Table 1 Number of people suffering damages from extreme weather events

Event	Hurricane Katrina	European HW 2003	Russian HW 2010
Deaths	1,337 min	E.g. FRA: 19,490, ITA: 20,089	∼55,000
# People high/extreme dmg	28,996		∼3,000
# People low/moderate dmg	66,059		
Direct economic losses	70–130 bn	FRA: \$1.1–4.4 bn, EU: \$12.3 bn	15 bn
Pop. of country	USA: 299 mn	FRA: ∼65 mn, ITA: 57.3 mn	Russia: ∼143 mn
Share of highly damaged pop.	∼0.01 ‰	FRA: ∼0.3 ‰, ITA: ∼0.35 ‰	∼0.52 ‰

High or extreme damages describe damages or destruction of all mobile and immobile assets. Low or moderate damages encompass temporary flooding, and light or moderate damages to structures (missing roof tiles, segments, or complete roofs, damaged mobile assets). The damage estimates for Hurricane Katrina only cover the state of Mississippi

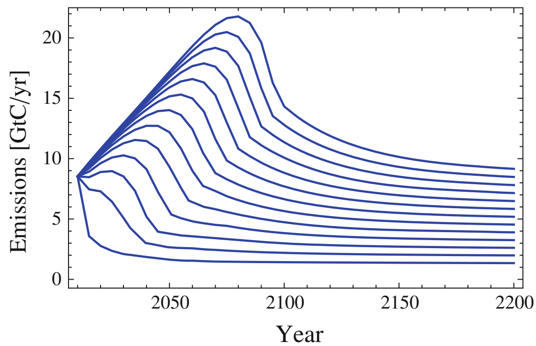


Fig. 7 CO_2 emissions over time for the 13 different concentration targets. The lowest target of 400 ppmv, of course, implies the lowest emissions

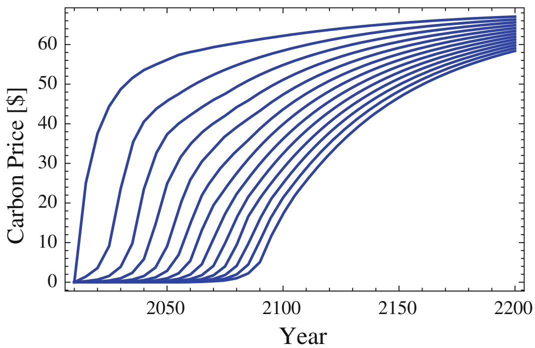


Fig. 8 (Current value) carbon price over time for the 13 concentration targets. The lowest target of 400 ppmv, of course, implies the highest carbon price

$\eta = 0.05$ is shown in Fig. 6. In the following we use a discretization of the parametrization with six cohorts at $i = 1,\ 1/2,\ 1/4,\ 1/8,\ 1/16,\ 1/32$, which also shown in Fig. 6.

Solving DICE with uncertainty about climate sensitivity and heterogeneous damages is numerically very intensive. Therefore, we sample the decision space by 13 concentration targets from 400 to 1,000 ppmv CO_2eq in steps of 50 ppmv. We associate a trajectory of the decision variables with each target by maximizing welfare for homogeneous damages and under certainty (uncertain parameters fixed at their expected value). The resulting 13 emission and carbon price trajectories are shown in Figs. 7 and 8. We then evaluate this sample of 13 targets and associated decision trajectories taking uncertainty, damage heterogeneity,

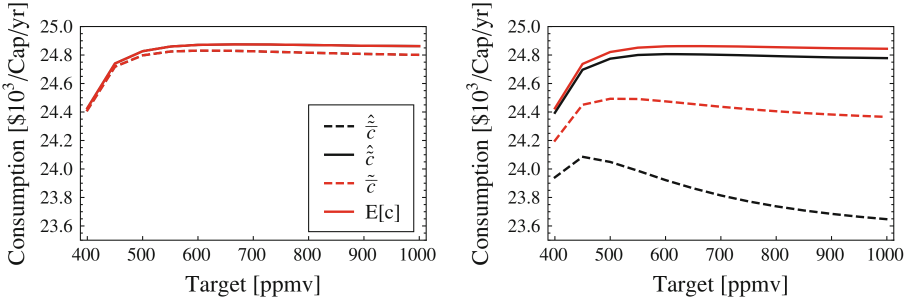


Fig. 9 ZGE consumption with (*black lines*) and without (*red lines*) inequality aversion, and with (*dashed lines*) and without (*solid lines*) risk aversion for different concentration targets. The legend in the *left graph* applies to the *right-hand graph* as well. The *left-hand graph* shows results for a perfectly homogeneous distribution of damages ($\eta = 1$), where inequality aversion doesn't have an effect (*black* and *red lines* coincide). The *right-hand graph* shows results for heterogeneous damages with $\eta = 0.05$. (Color figure online)

insurance markets and self-insurance into account. In other words, we test, which decision path fares best in terms of welfare under different circumstances such as heterogeneity, uncertainty and so on. Thereby, we assume that abatement costs are distributed homogeneously among the population. For most of this section, we also neglect income inequality in order to isolate the effect of damage heterogeneity. The interaction between income and damage inequality is discussed at the end of Sect. 3.1.

As we will see, sampling the decision space by 13 targets and evaluating them in different settings is not only more convenient, but also brings some added value. It allows us to analyze the differential effect of heterogeneity, insurance and so on across the policy space. We can also easily calculate opportunity costs of choosing suboptimal policies, which is necessary to assess whether changes in optimal decisions are accompanied by significant welfare improvements.

Parallel to Sect. 2, we will discuss the results without insurance, with insurance and with self-insurance in Sects. 3.1, 3.2, and 3.3, respectively.

3.1 No Insurance

For each target and associated control path, we calculate the discrete probability distributions on average consumption and damages. We then calculate heterogeneous damages and net consumption for each cohort in each state of the world. Subsequently we calculate expected utility for each cohort and aggregate to overall welfare.

Figure 9 shows the ZGE consumption levels with and without damage heterogeneity and for the different targets. Uncertainty, despite its considerable dispersion shown in Fig. 5, has a very small effect on welfare and consequently almost no differential effect on the different targets in the homogeneous case. The optimal target is lowered from 650 to 600 ppm but the resulting welfare improvement is negligible.

In contrast, uncertainty has a strong effect on welfare, if we introduce a pronounced heterogeneity described by $\eta = 0.05$ and shown in the right panel of Fig. 9. This effect is roughly doubled if utilitarian inequality aversion is assumed. The heterogeneity also has a strong differential effect: It makes high concentration targets less attractive by penalizing the bigger uncertainty they imply. The optimal target of 450 ppm has almost $500 higher ZGE consumption than the 1,000 ppmv target and implies substantially lower near-term emissions as can be seen in Fig. 7. The effect of inequality aversion without uncertainty, however, is

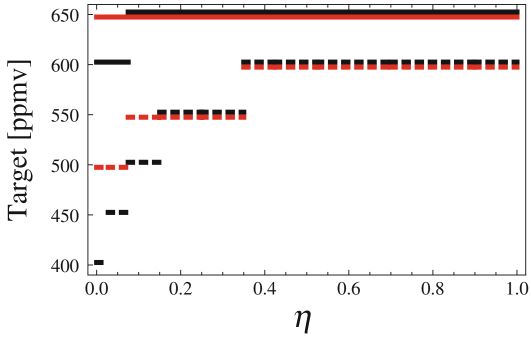
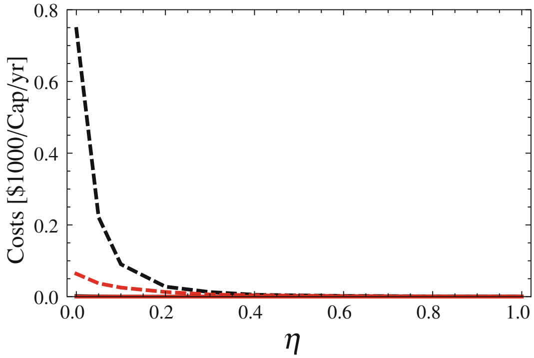


Fig. 10 The optimal concentration target as a function of the heterogeneity parameter η: with inequality aversion (*black*) and without (*red*); with risk aversion (*dashed lines*) and without (*solid line*) risk aversion, i.e. the same color code as in Fig. 9. (Color figure online)

Fig. 11 Consumption losses resulting from applying the optimal target under homogeneity and without uncertainty, which is 650 ppmv, rather than the optimal target with heterogeneity and uncertainty. The color code is the same as in Fig. 10. (Color figure online)



small. Hence the separate effects of uncertainty and damage heterogeneity are negligible, whereas the joint effect is substantial.

The optimal target as a function of the heterogeneity parameter η and with and without inequality aversion is shown in Fig. 10. The optimum decreases down to 400 ppmv for very heterogeneous damages with, and to only 500 ppmv without inequality aversion. Without uncertainty, inequality aversion has only a minor effect on the optimal target. It changes the optimal target from 650 to 600 ppmv for small $\eta < 0.1$. The welfare losses measured in ZGE that are incurred if the optimal target without heterogeneity and without uncertainty, which is 650 ppmv, is applied under heterogeneity and uncertainty, again as a function of η, are shown in Fig. 11. The losses from pursuing the 650 ppmv target are only severe if inequality aversion is assumed and heterogeneity is pronounced. For $\eta = 0.05$ these losses amount to roughly \$200 C&EQ&ZGE consumption/Cap/yr. This is about a third of the benefit of taking any action against climate change at all, i.e. not following business as usual.

We now perform a sensitivity analysis with respect to the parameter γ in the utility function. This parameter not only determines risk aversion but also the elasticity of inter-temporal substitution. Therefore the efficient policies to achieve the 13 concentration targets without uncertainty, which we use to structure the decision space, depend on γ. We take this into account and change the policies with the value of γ. We do not change the pure rate of time preference, though, so that the consumption discount rate changes with γ.

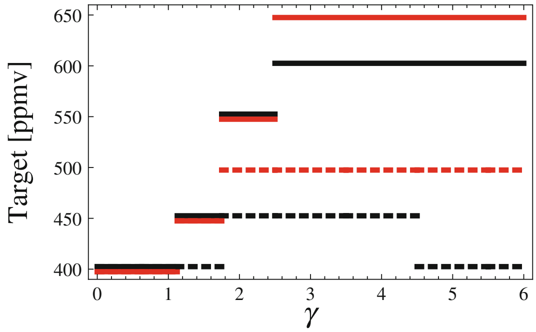


Fig. 12 The optimal concentration target as a function of the parameter γ. It is $\eta = 0.05$. The color code is the same as in Fig. 9. (Color figure online)

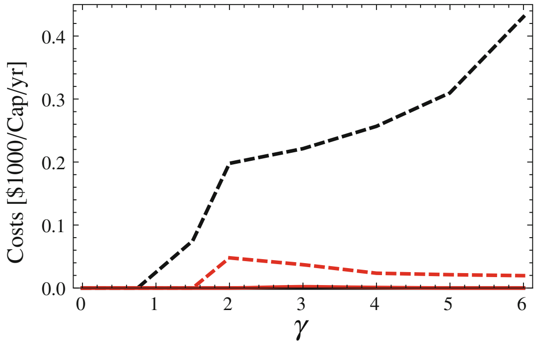


Fig. 13 ZGE consumption losses resulting from applying the optimal target under homogeneity and without uncertainty, which depends on γ, rather than the optimal target with heterogeneity and uncertainty. It is $\eta = 0.05$. (Color figure online)

The dependence of the optimal target on γ and for a heterogeneity parameter $\eta = 0.05$ is shown in Fig. 12. We note that the optimal target strongly decreases for decreasing γ even without uncertainty and inequality aversion. This is due to the fact that for decreasing γ, marginal utility decreases less rapidly, future consumption, which is higher than present consumption, becomes more valuable and hence future damages more painful, thus favoring strict targets (see also Nordhaus 2007). With uncertainty, the target decreases at high values of γ. This is due to the fact that a large γ also implies large risk aversion and thus favors strict targets, which lead to less risk. The flatness of the dashed curves between $\gamma = 1$ and $\gamma = 5$ is then explained by the two opposite effects canceling out: an increasing γ puts less emphasis on future consumption but at the same time puts more emphasis on risk. Figure 13 shows the losses resulting from choosing the optimal target without homogeneity and uncertainty rather than the truly optimal target. Again, without inequality aversion these losses can be neglected. Since the optimal target with inequality aversion does not change between $\gamma = 1$ and $\gamma = 5$, the increase of losses is due to a different valuation of same consumption losses and particularly the associated risk.

Up to now we have neglected income inequality in this section, in order to isolate the effect of damage heterogeneity. We now use a three-point discretization of the unequal income distribution shown in Fig. 14. It displays the income of individuals as a multiple of average income and is based on data from the World Development Report (WorldBank 2004). The index of individuals is not the same as the one for damage heterogeneity in Fig. 6, i.e. we do not assume perfect (anti-)correlation between relative damages and income. We rather consider two cases: (i) Relative damages are the same for all income classes. (ii) Relative damages are higher for low-income individuals. In both cases we assume that growth is distribution neutral, i.e. the income of all income classes grows at the same rate.

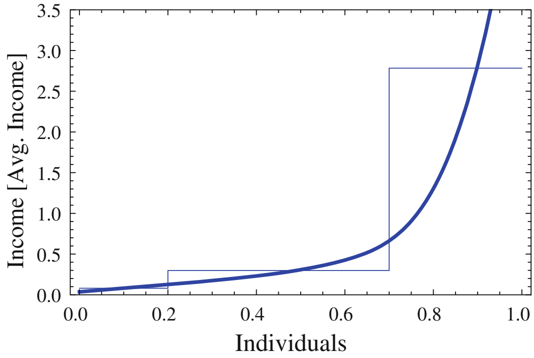


Fig. 14 Global income in units of average income sorted in descending order. The *thin straight lines* show the 3-point discretization. Income inequality will be discussed at the end of Sect. 3.1

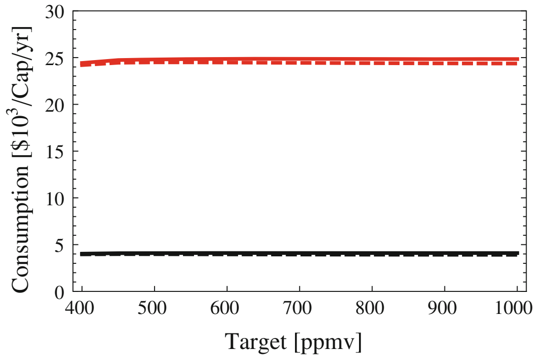


Fig. 15 ZGE consumption under income inequality. It is $\eta = 0.05$. The color code is the same as in Fig. 10. The *red lines* are the same as in the *right panel* of Fig. 9. (Color figure online)

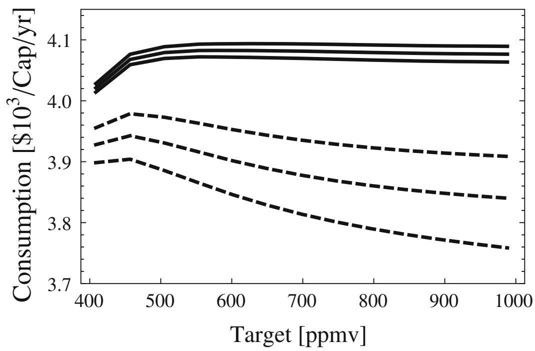


Fig. 16 ZGE consumption under income inequality and biased relative damages. Relative damages of the low income cohort are increased by 0, 20, and 40 % for the three *solid* and three *dashed lines*. *Lower lines* correspond to higher percentages

(i) Figure 15 shows the ZGE consumption for the different concentration targets. Inequality aversion now makes a huge difference and has a far bigger effect than risk aversion even for a strong damage heterogeneity described by $\eta = 0.05$. For a utilitarian, income inequality is obviously the primary concern. (ii) It can be expected that relative damages are higher for poor countries and low income classes (Yohe and Schlesinger 2002), amongst others because of their stronger dependence on vulnerable agriculture (Mendelsohn et al. 2006). Figure 16 shows the effect of such a negative relation between income and relative damages. More specifically, we increase relative damages of the poorest income class by 0, 20, and 40 % and exactly compensate this by decreasing relative damages of the richest income class thus keeping aggregate damages and consumption constant. The resulting effect on ZGE consumption is negligible without inequality aversion, the risk premium is the same as in Fig. 9 and therefore not shown. With inequality aversion, 40 % bigger relative damages on the low income class instead of homogeneous relative damages decrease the C&EQ&ZGE consumption by about \$150 or roughly 3.5 %. Hence, bigger relative risk for poor individuals notably increases the risk premium only under inequality aversion. Again, a substantial effect is only generated by compounding risk aversion and inequality aversion.

For the preceding results, we assumed that abatement costs are shared in proportion to income. Obviously, a progressive cost-sharing scheme, where percentage costs are higher for rich individuals than for poor ones, would have a welfare-enhancing re-distributional effect under inequality aversion and hence favor stricter stabilization targets.

3.2 Perfect Insurance Market

We now introduce an insurance market parallel to Sect. 2.2. More specifically, there is a contingent claims market for each time period and contingent claims are paid for and pay off in the same period. Endowments are determined by the 13 concentration targets. In contrast to Sect. 2.2, it is not sufficient to introduce one claim that pays off aggregate per capita damages in all states of the world characterized by aggregate per capita damages. Individual damages are now non-linear in aggregate damages, and individuals therefore want to buy different multiples of per capita damages in different states of the world.

Technically, for each of the 10×10 uncertain states of the world we introduce a contingent claim. We derive the first order conditions for each cohort and contingent claim analytically and furthermore impose market clearing conditions in each state of the world. The resulting system of equations is solved numerically.

Figure 17 shows the ZGE consumption with insurance. Comparing the results with the ones without insurance shows that insurance substantially reduces the risk premium both with and without inequality aversion. The reason, as discussed in detail in the analytical model in Sect. 2.2, is that the market efficiently distributes the risk over the entire population thereby reducing the individual and aggregate risk premium. This is also highlighted in Fig. 18, which shows how strongly the risk born by the low-i individuals is reduced. Actually, the most affected individuals carry a (slightly) lower than average risk due to their lower expected consumption and resulting higher absolute risk aversion. The reduction of individual risk premia also leads to a reduction of inequality, which explains the diminished effect of inequality aversion in Fig. 17.

In the presence of a perfect insurance market, the optimal targets under heterogeneity differ only very little from the ones under homogeneity, and the losses from not taking this into

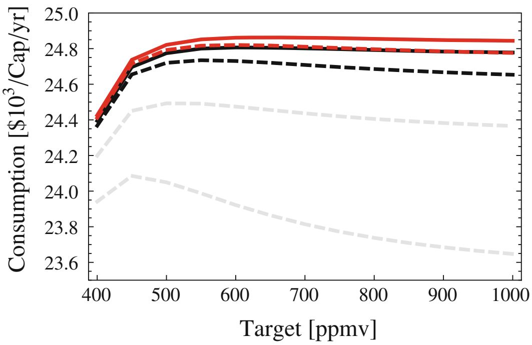
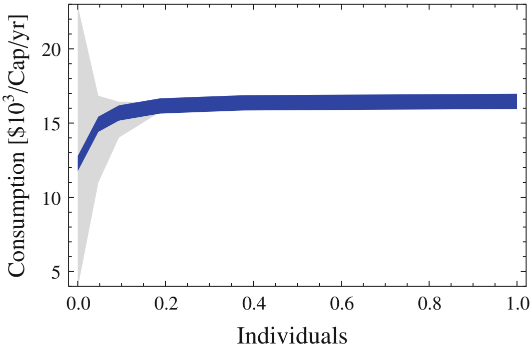


Fig. 17 The same as in Fig. 9 for the perfect insurance market solution. The solution without insurance is shown in *light gray* for comparison. (Color figure online)

Fig. 18 10 and 90 % quantiles of the PDF of consumption for the 600 ppmv target and for different individuals. The *blue area* is with insurance market and the *gray area* is without. The *upper edge* of the *gray area* is due to negative damages, i.e. benefits, from climate change



account are negligible. Hence, under the strong assumption that the distribution of damages over individuals is known and that a perfect insurance market can be installed for all periods, even strong heterogeneity would not have a significant impact on optimal climate policy.

3.3 Self-Insurance

Parallel to Sect. 2.3, we now assume that the heterogeneous individuals can adjust their savings levels to their individual damages. The representative agent of the homogenous case already uses self-insurance, or consumption smoothing, in reaction to future climate damages. Here we are interested in the effect of additional savings or dis-savings of individuals suffering heterogeneous damages. We assume a fixed interest rate, or approximately constant returns to scale, justified by the presumed smallness of aggregate additional savings. For each target, the time-varying interest rate is determined in the homogeneous and deterministic case, for which the policies were optimized,

$$P_t u'(y_t - E[D_t]) = e^{(r(\Delta t)-\beta)\Delta t} P_{t+\Delta t} u'(y_{t+\Delta t} - E[D_{t+\Delta t}]), \tag{16}$$

where P_t is the population at time t. At this interest rate, no additional savings are optimal under certainty and homogeneity. Zero additional savings are generally not optimal, though, if uncertainty is taken into account, even if damages remain homogeneous. Due to the smallness of the risk premia for homogeneous damages, though, optimal additional savings due to uncertainty are less than 1 % of overall savings for all targets and periods.

For heterogeneous damages, however, individual savings change considerably. Figure 20 shows additional savings in 2010. The most affected individuals save about 30 % more under the 400 ppmv target and about 45 % more under the 1,000 ppmv target, of which about 13 and 30 %, respectively, are due to deterministic consumption smoothing and the rest is due to precautionary saving. Aggregate savings increase by 2.9 and 1.5 %, respectively. These results are obtained by numerically solving independent consumption-savings problems with exogenous interest rate for the different cohorts.

The welfare effect of self-insurance is depicted in Fig. 19. Self-insurance, of course, improves welfare for all targets but particularly for high concentration targets. The improvement for 1,000 ppmv, for instance, is about \$500 ZGE. Self-insurance is particularly effective for lax targets because mitigation costs for these targets are low and thus consumption in early periods is high. Savings can shift this consumption to later periods with high damages.

An important caveat for these results is the assumption that increased savings do not lead to increased damages. The results would change dramatically if the savings of the affected were diminished by the same damage factor as their gross consumption. However, this is not quite

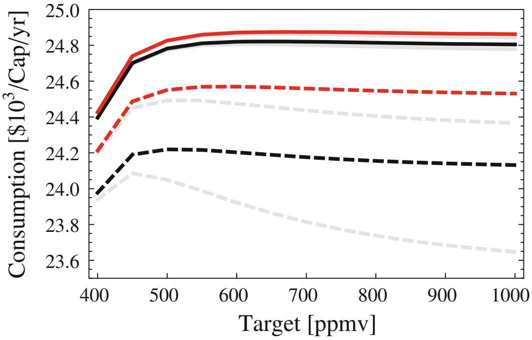


Fig. 19 The same as in Fig. 9 but including self-insurance. The results without self-insurance are shown in *light gray* for comparison. (Color figure online)

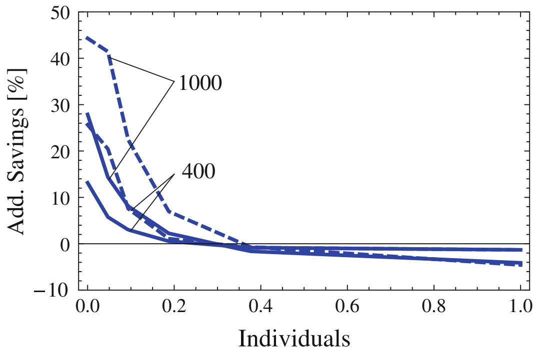


Fig. 20 Additional savings due to heterogeneity in 2010 for 2 targets, 400 and 1,000 ppmv, where the latter is the steeper curve. The heterogeneity parameter is $\eta = 0.05$

realistic either. In well functioning capital markets it should be possible to choose investments that are impacted at least only by the average damage factor across the population. Under this assumption, impacts on savings turn out not to have a significant effect on the results shown in Figs. 19 and 20. The truth presumably lies somewhere in between.

4 Conclusions

We have first demonstrated how climate damage heterogeneity and uncertainty can jointly have a significant effect on certainty- and equity equivalent damages. Numerical results from the DICE model later showed that this can lead to a substantially stricter optimal stabilization target if the damage heterogeneity is pronounced and even if the separate effects of uncertainty and heterogeneity were negligible. This latter result hinges on the presence of inequality aversion and thus emphasizes again the importance of equity considerations in climate change. Taking heterogeneity into account becomes more important the higher the relative risk aversion of the individuals.

Income inequality is presumably a far greater concern to a utilitarian than climate change. However, we showed to what extent it favors strict targets if there is a pronounced negative correlation between income and relative damages.

We then studied two “instruments” that can mitigate the effect of damage heterogeneity and uncertainty: insurance markets and self-insurance. A perfect insurance market leads to an efficient distribution of climate damages and the associated risk across the entire population. This reduces the risk premium essentially to the one for homogeneous damages. Some heterogeneity persists, though, because affected individuals have to pay insurance premia. The resulting effect on the optimal target under inequality aversion, however, turns out to be small in DICE. The presence of insurance markets thus would allow a weakening of the stabilization target and lead to substantial welfare gains. This indicates a large theoretical potential of insurance of climate damage uncertainty. However, the large time horizon and multiple market failures involved will certainly impede these markets.

Self-insurance, i.e. the increase in savings of the above-average impacted individuals, is not as effective as insurance markets in mitigating damage heterogeneity but still improves the attractiveness especially of less stringent concentration targets. The reason is that these targets imply low costs in the short run but high damages in the long run, which can partly be offset by increased savings. As a result, welfare differences between concentration targets of 500–1,000 ppmv CO_2eq vanished in DICE even for pronounced damage heterogeneity.

Improved information about who is affected by climate change and about the aggregate amount of damages decreases the effectiveness of insurance and increases the effectiveness of self-insurance resulting in an ambiguous overall effect of this information on welfare.

The following main caveat applies to the analysis. Its results are conceptual to the same extent as our parametrization of climate damage heterogeneity. Global estimates of climate damage heterogeneity and the associated uncertainty are not available. However, the results emphasize the need for such estimates and for subsequent analyses that explicitly take heterogeneity and uncertainty into account.

Acknowledgments Helpful comments by two anonymous reviewers are acknowledged.

References

Anthoff D, Tol RSJ (2009) The impact of climate change on the balanced growth equivalent: an application of FUND. Environ Resour Econ 43(3):351–367

Anthoff D, Tol RSJ (2010) On international equity weights and national decision making on climate change. J Environ Econ Manag 60(1):14–20

Anthoff D, Hepburn C, Tol RSJ (2009) Equity weighting and the marginal damage costs of climate change. Ecol Econ 68(3):836–849

Azar C (1999) Weight factors in cost–benefit analysis of climate change. Environ Resour Econ 13(3):249–268

Barriopedro D, Fischer EM, Luterbach J, Trigo RM, Garcia-Herrera R (2011) The hot summer of 2010: redrawing the temperature record map of europe. Science 332:220

Brakkes J, Bolt K, Braeuer I, ten Brink B, Chiabai A, Ding H, Gerdes H, Jeuken M, Kettunen M, Kirchholtes U, Klok C, Markandya A, Nunes P, van Oorschot M, Peralta-Bezerra N, Rayment M, Travisi C, Walpole M (2008) The cost of policy inaction: the case of not meeting the 2010 biodiversity target. European Commission, DG Environment

Cline WR (1992) The economics of global warming. Institute for International Economics, U.S., first edition, first printing edition

Constantinides GM (1982) Intertemporal asset pricing with heterogeneous consumers and without demand aggregation. J Bus 55(2):253–267

Dasgupta P (2008) Discounting climate change. J Risk Uncertain 37(2–3):141–169

Fankhauser S (1994) The economic costs of global warming damage: a survey. Glob Environ Change 4(4):301–309

Fankhauser S, Tol RSJ (2005) On climate change and economic growth. Resour Energy Econ 27(1):1–17

Fankhauser S, Tol R, Pearce D (1997) The aggregation of climate change damages: a welfare theoretic approach. Environ Resour Econ 10(3):249–266

Gollier C (2004) The economics of risk and time. The MIT Press, new edition

Gollier C (2005) Some aspects of the economics of catastrophe risk insurance. Technical Report 1409, CESifo Group Munich

Hirshleifer J (1971) The private and social value of information and the reward to inventive activity. Am Econ Rev 61(4):561–574

Hope CW (2006) The marginal impacts of CO2 CH4 and SF6 emissions. Integr Assess 6(5):537–544
IPCC (2011) Intergovernmental panel on climate change special report on managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge University Press, Cambridge
Kreps DM, Porteus EL (1978) Temporal resolution of uncertainty and dynamic choice theory. Econometrica 46(1):185–200
Kwasinski A, Weaver W (2005) Hurricane katrina's damage: assessment of power infrastructure for distribution, telecommunications and backup, with on-site data. Technical report, Grainger center for Electric Machinery and Electromechanics, University of Illinois Urbana-Champaign
Mendelsohn R, Dinar Al, Williams L (2006) The distributional impact of climate change on rich and poor countries. Environ Dev Econ 11(02):159–178
Mills E (2005) Insurance in a climate of change. Science 309(5737):1040–1044
Mirrlees JA, Stern NH (1972) Fairly good plans. J Econ Theory 4(2):268–288
Nordhaus WD (1994) Managing the global commons. MIT Press, Cambridge
Nordhaus WD (2006) Geography and macroeconomics: new data and new findings. Proc Natl Acad Sci USA 103(10):3510–3517
Nordhaus WD (2007) Critical assumptions in the stern review on climate change. Science 317(5835):201–202
Nordhaus WD (2008) A question of balance: weighing the options on global warming policies. Yale University Press, illustrated edition. ISBN 0300137486
Nordhaus WD (2009) An analysis of the dismal theorem. Cowles Foundation Discussion Paper No. 1686
Nordhaus WD (2010) Economic aspects of global warming in a post-Copenhagen environment. Proc Natl Acad Sci 107(26):11721–11726
Nordhaus WD, Popp D (1997) What is the value of scientific knowledge? an application to global warming using the PRICE model. Energy J 18(1):1–45
Nordhaus WD, Yang ZL (1996) A regional dynamic general-equilibrium model of alternative climate-change strategies. Am Econ Rev 86(4):741–765
Otto FEL, Massey N, van Oldenborgh GJ, Jones R, Allen MR (2012) Reconciling two approaches to attribution of the 2010 russian heat wave. Under revision for Geophysical Research Letters
Peck SC, Teisberg TJ (1993) Global warming, uncertainties and the value of information—an analysis using CETA. Resour Energy Econ 15(1):71–97
Roughgarden T, Schneider SH (1999) Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. Energy Policy 27(7):415–429
Stott PA, Stone DA, Allen MR (2004) Human contribution to the european heatwave of 2003. Nature 432: 610–614
TEEB (2010) The economics of ecosystems and biodiversity: mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. Technical report, 2010
Tol RSJ (2002) Estimates of the damage costs of climate change. Part 1: benchmark estimates. Environ Resour Econ 21(1):47–73
Tol RSJ (2003) Is the uncertainty about climate change too large for expected cost-benefit analysis. Clim Change 56:265–289
Ulph A, Ulph D (1997) warming, irreversibility and learning. Econ J 107(442):636–650
Webster M (2002) The curious role of "learning" in climate policy: Should we wait for more data. Energy J 23(2):97–119
Weitzman M (2009) On modeling and interpreting the economics of catastrophic climate change. Rev Econ Stat 91(1):1–19
Weitzman M (2010) GHG targets as insurance against catastrophic climate damages. Working Paper, http://www.economics.harvard.edu/faculty/weitzman/papers_weitzman
Wigley TML, Raper SCB (2001) Interpretation of high projections for global-mean warming. Science 293(5529):451–454
WorldBank (2004) World development report
Yohe G, Schlesinger M (2002) The economic geography of the impacts of climate change. J Econ Geogr 2(3):311–341
Zaitchik BF, Macalady AK, Bonneau LR, Smith RB (2006) Europe's 2003 heat wave: a satellite view of impacts and land-atmosphere feedbacks. Int J Climatol 26:743–769