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The economics (or lack thereof) of aerosol geoengineering

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Abstract Anthropogenic greenhouse gas emissions are changing the Earth's climate and impose substantial risks for current and future generations. What are scientifically sound, economically viable, and ethically defendable strategies to manage these climate risks? Ratified international agreements call for a reduction of greenhouse gas emissions to avoid dangerous anthropogenic interference with the climate system. Recent proposals, however, call for a different approach: to geoengineer climate by injecting aerosol precursors into the stratosphere. Published economic studies typically neglect the risks of aerosol geoengineering due to (i) the potential for a failure to sustain the aerosol forcing and (ii) the negative impacts associated with the aerosol forcing. Here we use a simple integrated assessment model of climate change to analyze potential economic impacts of aerosol geoengineering strategies over a wide range of uncertain parameters such as climate sensitivity, the economic damages due to climate change, and the economic damages due to aerosol geoengineering forcing. The simplicity of the model provides the

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advantages of parsimony and transparency, but it also imposes severe caveats on the interpretation of the results. For example, the analysis is based on a globally aggregated model and is hence silent on intragenerational distribution of costs and benefits. In addition, the analysis neglects the effects of learning and has a very simplistic representation of climate change impacts. Our analysis suggests three main conclusions. First, substituting aerosol geoengineering for CO_2 abatement can be an economically ineffective strategy. One key to this finding is that a failure to sustain the aerosol forcing can lead to sizeable and abrupt climatic changes. The monetary damages due to such a discontinuous aerosol geoengineering can dominate the cost-benefit analysis because the monetary damages of climate change are expected to increase with the rate of change. Second, the relative contribution of aerosol geoengineering to an economically optimal portfolio hinges critically on, thus far, deeply uncertain estimates of the damages due to aerosol forcing. Even if we assume that aerosol forcing could be deployed continuously, the aerosol geoengineering does not considerably displace CO_2 abatement in the simple economic optimal growth model until the damages due to the aerosol forcing are rather low. Third, substituting aerosol geoengineering for greenhouse gas emission abatement can fail an ethical test regarding intergenerational justice. Substituting aerosol geoengineering for greenhouse gas emissions abatements constitutes a conscious risk transfer to future generations, in violation of principles of intergenerational justice which demands that present generations should not create benefits for themselves in exchange for burdens on future generations.

1 Introduction

Anthropogenic emissions of greenhouse gases such as carbon dioxide (CO_2) have changed the Earth's radiative balance and are projected to cause sizeable climate change risks to current and future generations (Bernstein et al. 2008). The United Nations Framework Convention on Climate Change calls for a reduction of greenhouse gas emissions to "avoid dangerous anthropogenic interference with the climate system" (UNFCCC 1992). Reducing the climate forcing through abating greenhouse gas emissions tackles the risk of anthropogenic climate change at the root cause. However, abating greenhouse gas emission acts slowly on the climate system due to the sizeable inertia of the carbon cycle, and it requires sizeable investments (Barker et al. 2007; Keller et al. 2007; Nordhaus 2008).

One strategy that has been proposed to efficiently reduce the inertia and cost problems of greenhouse gas abatement strategies is to geoengineer the climate system (e.g., Keith 2000; COSEPUP 1992; Carlin 2007; Crutzen 2006; Teller et al. 2003; Wigley 2006; Blackstock et al. 2009). Among all geoengineering strategies, injecting aerosol precursors into the stratosphere to increase Earth's albedo is evaluated as one of the cheapest and most efficient in reducing global temperatures (Nordhaus 2001; Wigley 2006; Shepherd et al. 2009).

Past analyses of the decision to deploy geoengineering strategies often assume that geoengineering strategies pose negligible risks. For example, Nordhaus (1992) analyzes the economics of deploying a geoengineering strategy that is "environmentally benign." Wigley (2006) states that "deliberately adding aerosols or aerosol precursors to the stratosphere ... present minimal climate risks." Faced with a hypothetical choice between the slow and expensive option of CO_2 abatement and a fast, cheap, and low-risk option of geoengineering, many studies conclude that substituting geoengineering for some fraction of the CO_2 abatement would pass an economic cost-benefit test. Carlin (2007), for example, concludes that "the most effective and efficient solution would be to use a concept long proven by nature to reduce the radiation reaching the earth by adding particles optimized for this purpose to the stratosphere to scatter a small portion of the incoming sunlight back into space." Crutzen (2006) states that "if positive effects are greater than negative effects, serious considerations should be given to the albedo modification scheme." Wigley (2006), states that "a relatively modest geoengineering investment ... could reduce the economic and technological burden on mitigation substantially, by deferring the need for immediate or near-future cuts in CO_2 emissions."

It is important to recall that the assumption underlying many studies that geoengineering strategies are indeed benign and pose "minimal climate risks" (Wigley 2006) is, at this time, a rather debatable point. In a recent report, Blackstock et al. (2009) argues that "we currently understand very little about either the potential utility or the risks of reducing absorbed solar radiation" and suggests that "unanticipated negative impacts on human and ecological systems could overshadow the expected benefits."

One general problem with aerosol geoengineering is that it attempts to balance the radiative forcing of CO_2 with the counterforcing by stratospheric aerosols. These two forcings have vastly different climate response times because stratospheric aerosols have a life-time of a few years (Robock 2000) while CO_2 in the atmosphere has a lifetime of centuries to millennia (Archer and Brovkin 2008). A failure to maintain the aerosol counterforcing (for example in the case of a war, a breakdown of an international agreement, or the discovery of sizable negative effects due to the aerosol forcing) would lead to an abrupt warming with rates that are unprecedented for modern human societies and would likely cause sizeable economic damages (Lempert et al. 2000; Matthews and Caldeira 2007; Nordhaus 1994a). A second risk of aerosol geoengineering is that the resulting polar ozone depletion (Tilmes et al. 2008) would damage natural and managed ecosystems and human health (Solomon 2008). A third risk is that aerosol geoengineering will not counteract ocean acidification, which is caused by the reaction between CO_2 and sea water (Shepherd et al. 2009). Ocean acidification can negatively impact coral reefs and pelagic populations that depend on them (Feeley et al. 2004; Stoll et al. 2007). Finally, variations in the concentration of stratospheric aerosol affect the properties of climate system components such as El Niño (Adams et al. 2003), precipitation- and temperature-patterns (Rasch et al. 2008; Trenberth and Dai 2007), and the Asian and African summer monsoon (Robock et al. 2008). This brief discussion of geoengineering risks is certainly not exhaustive (cf. Jamieson 1996; Keith 2000; Robock 2008; Schneider and Broecker 2007), but arguably sufficient to make the point that an analysis of geoengineering strategies needs to account for geoengineering risks.

Here we use a simple integrated assessment model (IAM) of climate change to analyze climate risk management strategies via CO_2 abatement and aerosol geoengineering. Specifically, we modify an existing IAM (Nordhaus 2008) by (i) adding a more refined climate model that results in an improved representation of abrupt climate change and observational constraints (Kriegler 2005; Urban and Keller 2009, 2010), (ii) approximating the effects of uncertainty about future monetary discount rates (Newell and Pizer 2004), climate sensitivity, and CO_2 abatement costs, (iii) representing aerosol geoengineering as including a potential failure to sustain the aerosol forcing ("intermittent geoengineering") as well as potential negative side effects of the geoengineering forcings, and (iv) considering the problem of choosing an optimal mix of CO_2 abatement and aerosol geoengineering. The model is, of course, only a simplified representation of the coupled natural and human systems. For example, the model neglects likely important features such as future learning and induced technological change (cf. Keller et al. 2008a; Nordhaus 2008). In addition, we compare a limited set of strategies. The model does allow us, however, to draw consistent conclusions from a set of clearly stated and transparent assumptions.

Our results are consistent with previous claims that substituting geoengineering for CO_2 abatement is an economically efficient strategy if (i) the probability of intermittent aerosol geoengineering is relatively low and (ii) the economic damages due to the geoengineering forcing are negligible (cf. Carlin 2007; Nordhaus 1992). While our analysis concurs with these previous studies, we focus on the question of what happens if these two deeply uncertain assumptions fail. We expand on previous studies in four main ways. First, we show that substituting aerosol geoengineering for CO_2 abatement can be an economically inefficient strategy for arguably reasonable assumptions about the probability of intermittent aerosol geoengineering as well as potential damages due to aerosol injections into the stratosphere. Second, we demonstrate how substituting aerosol geoengineering for CO_2 abatement can increase the ranges of climate change and economic outcomes. Third, we illustrate key intertemporal risk transfers due to the substitution of aerosol geoengineering for CO_2 abatement. Last, but not least, we put the economic analysis in an ethical perspective by discussing intergenerational justice aspects of the analyzed strategies.

2 Methods

We use the Dynamic Integrated model of Climate and Economy (DICE-07, Nordhaus 2008) as a starting point. The model couples a Ramsey (1928) economic optimal growth model with simple representations of the global carbon cycle, the climate system, and economic impacts of climate change and investments in climate change mitigation strategies. The model components and their couplings are briefly outlined below. An excellent and detailed model description is given in Nordhaus (2008). The model implementation is available from the first author upon request.

2.1 The economic model

The objective of the stylized decision maker in the model is to maximize an objective function W that is the discounted utility of consumption U over time summed over a finite time horizon of T time-steps according to:

$$W = \sum_{t=0}^{T-1} U[c(t), L(t)]R(t). \tag{1}$$

The utility is used here as a measure of well-being of the population. The utility can be interpreted as well-being or the satisfaction of preference (Bernoulli 1738; Broome 1991; Kahneman and Sugden 2005). In the model, the utility is a function of the exogenous population $L(t)$, the per capita consumption $c(t)$, and the elasticity of marginal utility of consumption α. Specifically, the utility function is defined as:

$$U[c(t), L(t)] = L(t)\left(\frac{c(t)^{(1-\alpha)} - 1}{1-\alpha}\right). \tag{2}$$

$R(t)$ in Eq. 1 is the discount factor, which is a function of the pure rate of social time preference $\rho(t)$:

$$R(t) = (1 + \rho(t))^{-(t-t_0)}. \tag{3}$$

Consumption is the fraction of output $Q(t)$ that is not devoted to investment in capital stock $I(t)$:

$$C(t) = Q(t) - I(t). \tag{4}$$

$I(t)$ is the first decision variable in the model (in addition to CO_2 abatement and aerosol geoengineering, discussed below). The investments over time are chosen to maximize the objective function (Eq. 1). Output is defined by a modified Cobb–Douglas production function depending on capital stock $K(t)$, the exogenous factors $L(t)$ and technology $A(t)$, and the elasticity of output with respect to capital γ:

$$Q(t) = \Omega(t)\Lambda(t)A(t)K(t)^{\gamma}L(t)^{(1-\gamma)}. \tag{5}$$

The economic impacts of climate change and the investment in CO_2 emissions abatement are represented by the scaling factors Ω and Λ, respectively (described below).

Climate damages $D(t)$ are a function of global mean surface temperature changes that are used as a proxy measure for the magnitude of anthropogenic climate change. Climate damages affect the economic output through the scaling factor Ω:

$$\Omega(t) = 1/(1 + D(t)). \tag{6}$$

Abatement costs $TC(t)$ are expressed as a fraction of the world output. They affect the output via the scaling factor Λ:

$$\Lambda(t) = 1 - TC(t). \tag{7}$$

The parameterizations for $D(t)$ and $TC(t)$ are discussed below (Eqs. 15 and 16).

Investment contributes to the capital stock of the next period and depreciates at a constant rate (δ_K) over time:

$$K(t) = I(t-1) + (1 - \delta_k)K(t-1). \tag{8}$$

Industrial CO_2 emissions depend on the economic output, the exogenously determined carbon intensity of economic activity ($\sigma(t)$), and the fractional CO_2 abatement rate (the second decision variable $\mu(t)$), according to:

$$E_{Ind}(t) = \sigma(t)[1 - \mu(t)]A(t)K(t)^{\gamma}L(t)^{(1-\gamma)}. \tag{9}$$

The endogenously determined industrial CO_2 emissions and the exogenously evolving land-use emissions (E_{Land}) define the total anthropogenic CO_2 emissions:

$$E(t) = E_{Ind}(t) + E_{Land}(t). \tag{10}$$

2.2 The carbon cycle model

The CO_2 emissions act to increase the atmospheric CO_2 stock (M_{At}). The response of the global mean carbon cycle to this anthropogenic perturbation is approximated by a first-order, linear, three-box model with reservoirs representing the atmosphere, a pool of the mixed biosphere and the upper ocean, and the deep ocean. A fraction of the atmospheric CO_2 stock (M_{At}) is transported to the upper ocean carbon pool (M_{Up}), which is absorbed by the deep ocean pool (M_{Lo}) according to:

$$M_{At}(t) = E(t-1) + \varphi_{11} M_{At}(t-1) + \varphi_{21} M_{Up}(t-1), \tag{11}$$

$$M_{Up}(t) = \varphi_{22} M_{Up}(t-1) + \varphi_{32} M_{Lo}(t-1) + \varphi_{12} M_{At}(t-1), \text{ and} \tag{12}$$

$$M_{Lo}(t) = \varphi_{33} M_{Lo}(t-1) + \varphi_{23} M_{Up}(t-1). \tag{13}$$

The φ_{ij} parameters control transfer rates of CO_2 between reservoirs. This simple linear approximation of the global carbon cycle is numerically efficient but neglects potentially important effects such as the decreasing CO_2 uptake rate in response to the depletion of the oceanic buffering capacity (cf. Joos et al. 1999; Schulz and Kasting 1997).

2.3 The climate model and geoengineering

Atmospheric CO_2 levels above the pre-industrial level ($M_{At}(1750)$) cause a net radiative climate forcing according to:

$$F(t) = F_{2xCO_2} \left\{ \log_2 \left[\frac{M_{At}(t)}{M_{At}(1750)} \right] \right\} + F_{Ex}(t) - F_{Geo}(t), \tag{14}$$

where $F_{2xCO_2} = 3.7\ \mathrm{Wm}^{-2}$ is the radiative forcing for a doubling of atmospheric CO_2 concentrations, and F_{Ex} represents exogenously specified radiative forcing from climate forcings besides CO_2 (e.g., methane or aerosols). The first two terms in the right side of the Eq. 14 are related to the anthropogenic greenhouse gas forcings, given in CO_2 equivalent. The last term in the Eq. 14, F_{Geo} is the forcing due to the aerosol geoengineering injection in the stratosphere.

Evaluating the impacts of this radiative climate forcing on the global mean surface temperature change (T_{At}) requires a climate model. The original DICE-07 model (Nordhaus 2008) uses a computationally highly effective and simple two-box climate model. This two-box model can provide a reasonable approximation to the decadal-scale climate change response to anthropogenic forcings (Nordhaus 1994b). Due to the coarse spatial resolution, the model is, however, numerically very diffuse and represents rather poorly the effects of the fast changes in radiative forcing that would occur in the case of an abrupt termination of aerosol geoengineering forcing (cf. Matthews and Caldeira 2007). We address this problem by implementing the DOECLIM climate model by Kriegler (2005) in the DICE model. The DOECLIM model (Kriegler 2005) is an energy balance model consisting of four boxes representing land, troposphere over land, troposphere over sea, and ocean mixed layer coupled to a one-dimensional diffusive equation representing the deeper ocean a with a depth of 4000 m. We start the DOECLIM model at an assumed preindustrial

Table 1 Types of parametric uncertainty, the adopted probability density function, and the number of samples used to define the States of the World (SOW)

Type of uncertainty	Probability density function	Number of SOWs
Climate sensitivity	Synthesis of the general properties as reviewed by Knutti and Hegerl (2008) (see Fig. 2 and text)	50
Abatement costs	Uniform distribution of b1 in Eq. 16 of +− 30% DICE07 value.	7
Damages	(Nordhaus 1994a)	18

The strategies are evaluated across all SOW (n = 6,300, defined by a cube with 50 × 7 × 18 equally likely samples assuming an uncorrelated joint probability density function)

equilibrium state and then use historical radiative forcing (cf. Urban and Keller 2010) before coupling it with the carbon cycle and economic models for future projections.

2.4 Representation of uncertainties

We approximate the effects of parametric uncertainty about three model parameters: (i) the climate sensitivity, (ii) future economic damages of climate change, and (iii) the cost of CO_2 abatement. We approximate the probability density function of the relevant parameters with discrete samples representing equally likely States Of the World (SOW) (cf. Keller et al. 2004; Nordhaus and Popp 1997) (Table 1). We also approximate the effect of uncertainty about future monetary discount rates by choosing the social rate of time preference and the elasticity of marginal utility of consumption such that the monetary discount rate in the model approximates a projection of the certainty equivalent monetary discount rate (Newell and Pizer 2004) (Fig. 1). The representations of these effects of parametric uncertainty are detailed below.

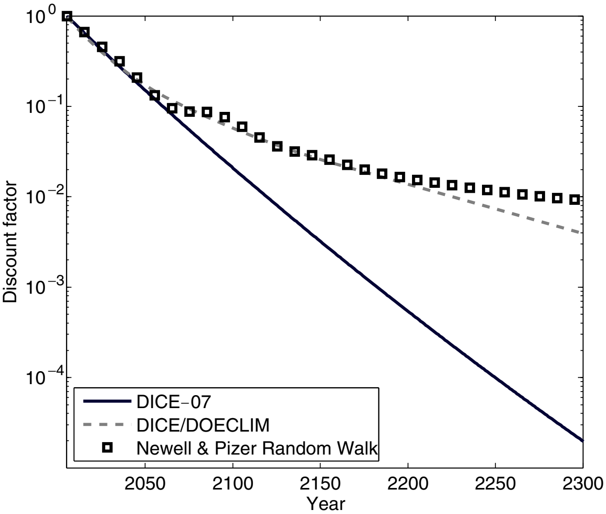

Fig. 1 Monetary discount factor for the original DICE-07 model (Nordhaus 2008) (*straight line*), the estimate of Newell and Pizer (2004) for a random walk model (*squares*), and the fitted curve (*dashed gray line*) used in this study. The monetary discount factors are calculated from the optimal per capita consumption trajectory for a business-as-usual strategy and using a value for the elasticity of marginal utility of consumption (α) of 1.1

2.4.1 Climate sensitivity

Climate sensitivity represents a key source of uncertainty in future climate predictions (Knutti and Hegerl 2008; Urban and Keller 2010). Current climate sensitivity estimates are deeply uncertain (Knutti and Hegerl 2008; Frame et al. 2005). Deep uncertainty refers to the situation when the estimates depend strongly on subjective and divergent prior assumptions (Keller et al. 2008b; Lempert et al. 2002; Lempert 2002). Current climate sensitivity estimates can be typically summarized by modes roughly between one and four K, a positive skewness (i.e., a fat right tail), and a considerable probability mass up to roughly 10K. We represent these characteristics using an empirical probability density function (pdf) (Fig. 2). We sample this pdf using 50 stratified (and equally likely) Latin Hypercube samples (Helton and Davis 2003). Similar to Yohe et al. (2004) we account for the positive correlation between estimates of climate sensitivity and the vertical ocean diffusivity (cf. Urban and

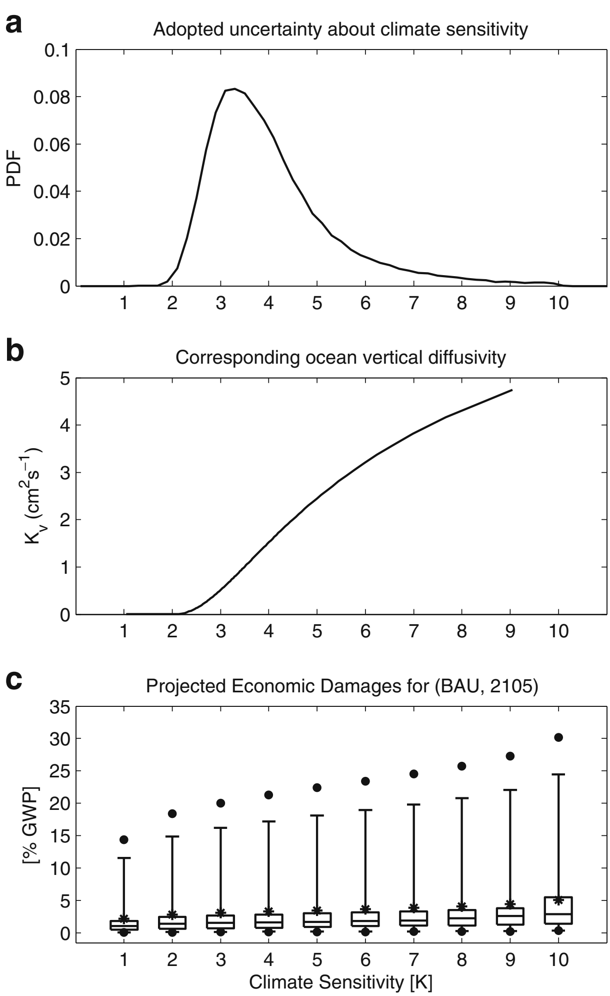

Fig. 2 Representation of the uncertainty about climate sensitivity (panel **a**) (see Table 1 and text), the correlation between the vertical ocean diffusivity K_v and climate sensitivity (panel **b**) (cf. Urban and Keller 2010), and the resulting uncertainty about the economic damages of climate change (for a business-as-usual scenario in 2105) accounting for the combined effects of uncertainty about climate sensitivity and the economic damage function (panel **c**)

Keller 2009) using a nonlinear mapping between climate sensitivity and ocean diffusivity derived from a model fit to the observations.

2.4.2 Economic damages of climate change

Estimates of current and future economic damages of climate change are still deeply uncertain (Keller et al. 2008b; Nordhaus 2008; Tol 2008b). In the DICE-07 model (Nordhaus 2008), economical damages are approximated as a square function of the deviation of the global mean surface temperature from the preindustrial value. This parameterization neglects the likely important effects of the rate of climate change on economic impacts (Lempert et al. 2000; Nordhaus 1994a; Tol 1996). The potential biases introduced by neglecting the rate-dependency of climate change impacts are especially severe for the analysis of aerosol geoengineering strategies. This is because aerosol geoengineering can lead to very fast climate changes (Matthews and Caldeira 2007). We address this problem by modifying a rate-dependent damage function following Lempert et al. (2000) to yield:

$$D(t) = \tanh\left(\alpha_1\left[\frac{\Delta\bar{T}_5(t)}{3^{\circ}C}\right]^2 + \alpha_2\left[\frac{\Delta T(t) - \Delta\bar{T}_{30}(t)}{0.35^{\circ}C}\right]^4\right) + \theta\frac{F_{Geo}}{F_{2xCO_2}}. \tag{15}$$

In this equation $D(t)$ represents the economic damages due to climate change measured as a fraction of output. The damages are the nonlinear function of $\Delta T(t)$, the annual global mean surface temperature change, ΔT_5 and ΔT_{30}, the 5-year and 30-year running averages of $\Delta T(t)$, respectively, the relative radiative geoengineering forcing F_{Geo}/F_{2xCO_2}, and the scaling factors α_1, α_2, and θ. θ represents the economic damages due to injection of aerosols into the stratosphere in percent of GWP for a radiative forcing F_{Geo} that offsets the radiative forcing due to a doubling of the atmospheric CO_2 concentration F_{2xCO_2}. The terms in the argument of the hyperbolic tangent (tanh) function are the ones defined in Lempert et al. (2000). These terms represent economic damages due to relatively short- and long-term climate variations, respectively. We add the hyperbolic tangent to constrain climate change damages to be less than the global gross world product. This has negligible effects for low and intermediate damages, but ensures numerical stability for the model structure given very high damages.

We estimate the coefficients α_1 and α_2 in the damage model (Eq. 15) by fitting the damage function to expert assessments of economic damages reported by Nordhaus (1994a) (Table 2). Specifically, we fit the median estimates of the economic impacts on the global output from the 18 expert assessments reported by Nordhaus (1994a) for a 3 K and a 6 K temperature increase by 2090. It is important to stress that this simple approach leaves the resulting parameterization sensitive to the choice of experts assessed and to the wording of the assessment. It also neglects new information identified since the assessment. As additional constraints, we limit the economic damages in 2005 to be less than or equal to two percent of the GWP. Note that these damage estimates focus mainly on the impacts due to climate change and are silent on the damages due to increased CO_2 concentrations, for example via the effects of changes in the oceanic acidity on marine ecosystems (Feely et al. 2004; Stoll et al. 2007). The resulting damage estimates are illustrated for a business-as-usual scenario for the year 2105 in Fig. 2. The damages due to aerosol climate forcing

Table 2 Parameters α_1 and α_2 in the damage function (Eq. 13) fitted to the median expert assessments reported in Nordhaus (1994a)

Expert number	Scenario A [percent GWP]	Scenario C [percent GWP]	α_1	α_2	RMSE
1	1.3	2.6	7.2e-03	1.8e-20	0.44
2	1.3	3.8	1.0e-02	6.4e-20	0.24
3	0.3	0.8	2.2e-03	7.1e-07	0.07
4	1.5	4.0	1.1e-02	1.8e-20	0.34
5	16	30	8.4e-02	4.5e-19	6.02
6	1.9	6.0	1.6e-02	1.4e-20	0.27
7	2.5	5.0	1.4e-02	3.7e-20	0.85
8	21	62	1.7e-01	8.3e-19	3.74
9	1.5	4.0	1.1e-02	7.3e-21	0.34
10	5.0	15	4.0e-02	3.0e-19	0.85
11	1.8	6.4	1.7e-02	4.1e-20	0.13
12	2.0	6.0	1.6e-02	1.8e-20	0.34
13	3.0	6.0	1.7e-02	8.4e-20	1.03
14	0.0	2.0	5.1e-04	4.0e-04	0.07
15	2.0	10	2.1e-02	4.9e-04	0.07
16	0.5	3.5	5.4e-03	3.3e-04	0.03
17	0.3	1.0	2.4e-03	2.2e-05	0.05
18	2.0	20	2.0e-02	2.8e-03	0.06

The fits are derived by minimizing the root mean squared errors (RMSE) between the damage function and the expert estimates using a global minimization algorithm (Storn and Price 1997). Shown are results for the scenario A (3K warming by 2090) and the scenario C (6K warming by 2090)

cannot be estimated from the Nordhaus (1994a) expert assessment as they were not part of the expert assessment. We hence use a sensitivity study over a subjectively chosen range of θ between zero and two percent.

2.4.3 Costs of reducing CO_2 emissions

The costs of CO_2 abatement (TC, expressed as a fraction of GWP) are approximated by:

$$TC(t) = b_1 \mu^{b_2}, \tag{16}$$

where the exponent b_2 determines the nonlinearity and b_1 is a scaling factor. Following Nordhaus and Popp (1997), we represent the uncertainty about the abatement costs by different parameter values b_1. Specifically, we sample from a uniform distribution centered on the original value in the DICE-07 model that covers ± 30 percent of this value. Given the rather low estimates of the costs of deploying aerosol geoengineering, (cf. Barrett 2008), we neglect this term.

2.5 Future monetary discount rates

The Ramsey-style economic optimal growth model maximizes a discounted sum of current and future utilities (Eq. 1). Two key parameters representing important value judgments in this framework are the social rate of time preference $\rho(t)$ and the elasticity of marginal utility of consumption α (Bradford 1999; Broome 1994;

Ludwig et al. 2005; Nordhaus 2008). These two quantities are linked in the solution to a Ramsey-style optimal growth model by:

$$r(t) = \rho(t) + \alpha g(t), \tag{17}$$

(cf. Nordhaus 1994b) where $r(t)$ is the risk free monetary discount rate and $g(t)$ is the growth rate of per capita consumption. One common method of choosing these two parameters is to adopt a "descriptive approach" where observed quantities in the economic system are used to infer consistent parameter values (Anthoff et al. 2008; Nordhaus 2008; Keller et al. 2007). The logic behind this approach is to interpret an observed monetary discount rate as the result of an optimization decision reasonably well described by the Ramsey model and then to analyze climate change strategies in view of these estimated value judgments. We follow this approach and choose $\rho(t)$ and α values to approximate projected certainty equivalent monetary discount rates based on a random walk model reported by Newell and Pizer (2004). Specifically, we choose a constant α and an exponentially decaying $\rho(t)$ to fit the projected monetary discount factor in a least square sense (Fig. 1).

2.6 Numerical solution technique

The integrated assessment model defines an optimization problem to determine the constraint optimal trajectories of investments ($I(t)$), relative CO_2 abatement (μ), and relative aerosol geoengineering (discussed below). We identify an optimal trajectory for all the 6300 States of the World (Table 1) using a global optimization technique as described in McInerney and Keller (2008). We use a finite time horizon of 590 years and a ten-year time step size. Further extending the numerical time horizon had negligible effects on the optimal strategies of the analyzed time window of 2005 to 2150.

3 Analyses

We use this model to analyze four strategies.

1) BAU: A hypothetical reference case of a business-as-usual (BAU) scenario without any climate control (i.e., neither CO_2 abatement nor aerosol geoengineering).
2) Optimal abatement: This strategy only uses CO_2 abatement (and no aerosol geoengineering) to maximize the objective function.
3) Continuous and discontinuous aerosol geoengineering: This strategy only uses aerosol geoengineering and no CO_2 abatement. For this analysis we analyze two cases: (a) continuous and (b) discontinuous aerosol geoengineering. In the continuous aerosol geoengineering case, stratospheric sulfite aerosols are released in the atmosphere in the years 2015 to perfectly offset the anthropogenic climate forcings to the levels of the year 1750 (Fig. 3a) (Note that this approximation neglects the sizeable uncertainty about the radiative properties of aerosols as discussed, for example, in Urban and Keller 2010). In the discontinuous aerosol geoengineering case, the aerosol forcing is discontinued in a specific year, which we chose for this illustrative analysis to be the year 2065 (Fig. 3a).

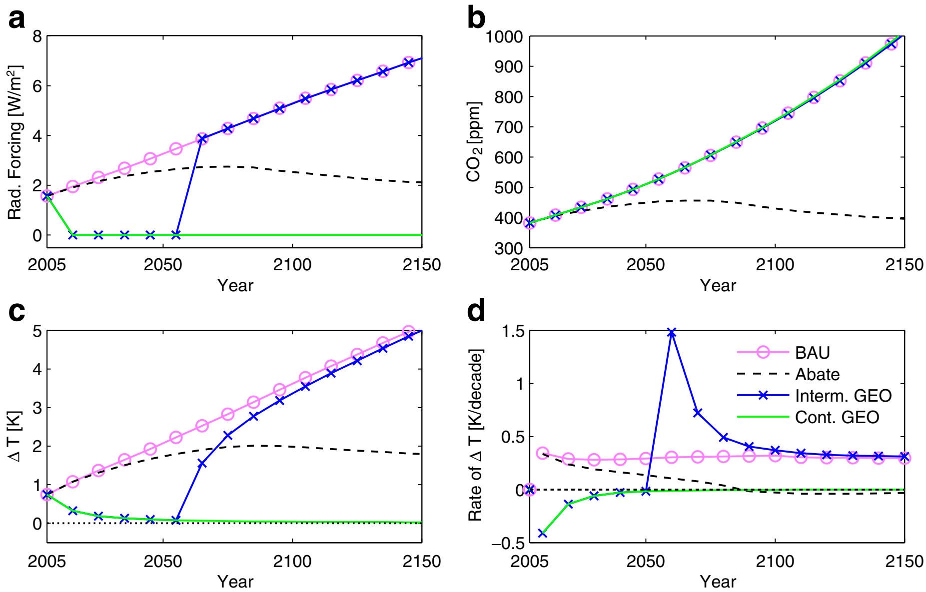

Fig. 3 Radiative forcing (panel **a**), global mean atmospheric CO_2 (panel **b**), global mean surface temperature change (panel **c**), and the rate of global mean surface temperature change (panel **d**) for BAU (*circles*), abatement (*dashed line*), intermittent geoengineering (*crosses*), and continuous geoengineering (*solid line*). Note that these results neglect potential economic damages due to aerosol geoengineering forcing

Technically, F_{Geo} is a binary exogenous variable in the model. Considering the case of either geoengineering or CO_2 abatement simplifies the analysis of the results and represents some of the current discussions about aerosol geoengineering. However, analyzing this simplified case also provides important insights. Of course, this simplified analysis framework does not address the question of a combined aerosol geoengineering/CO_2 mitigation strategy. This strategy is analyzed below.

4) Combined CO_2 abatement and aerosol geoengineering strategy: This strategy uses an optimal (in the framework of the highly simplified nature of the integrated assessment model) mix of CO_2 abatement and aerosol geoengineering. Technically, we add geoengineering as an optimization variable where F_{Geo} can acquire any value between zero and 100 percent of anthropogenic climate forcing. The optimization algorithm then identifies the optimal time trajectories of abatement and geoengineering that jointly maximize the objective function (Eq. 1). Results from this mixed strategy are analyzed in Section 4.3.

4 Results and discussion

We first discuss the physical and economic impacts of the considered strategies neglecting parametric uncertainty and the economic damages due to radiative geoengineering forcing (i.e. we set the parameter θ in Eq. 15 to zero). We then analyze the economic performance of the different strategies with the effects of the considered parametric uncertainties and with different choices of the economic damages due to geoengineering forcings.

4.1 Physical impacts

The considered scenarios result in strongly diverging climate forcings, atmospheric CO_2 concentrations, global mean temperature changes, and rates of global mean temperature changes (Fig. 3). At the end of this century, the radiative forcing increases to more than 4 Wm^{-2} for the business-as-usual scenario (Fig. 3). This results in a temperature rise by an average of 3.5 K, and an atmospheric CO_2 concentration of roughly 700 ppm. The resulting rate of global mean temperature change is around 0.4 K per decade. For the abatement strategy, the peak of atmospheric CO_2 concentration is reached in 2075 with roughly 450 ppm. The rate of temperature change is highest at the beginning of the simulation (about 0.3 K per decade), and decreases approximately linearly with time until 2095. The temperature increase relative to the preindustrial value is less than 2 K for the best-guess parameter values. For the geoengineering strategy, the atmospheric CO_2 concentrations are close to the business-as-usual strategy (around 700 ppm in 2100), but the temperatures diverge strongly. Temperatures for the geoengineering strategies start to decrease towards preindustrial values in 2015 due to the decrease in radiative forcing through aerosol injection. For the continuous geoengineering forcing scenario, the radiative forcing is reduced to preindustrial values and the global mean temperatures approach the preindustrial values within a few decades. For the intermittent geoengineering scenario, the aerosol forcing is discontinued in the year 2065, and the global mean temperature increases quickly, closely approximating the BAU scenario within a few decades. Both geoengineering scenarios result initially in negative rates of temperature change. The intermittent geoengineering case results in warming rates of roughly 1.5 K/decade, far exceeding the rates for the business-as-usual case (Fig. 3d).

4.2 Economic impacts

The differences in physical properties across the considered strategies result in different economic impacts (Fig. 4). The economic damages of climate change (Fig. 4a) increase from less than one percent in 2005 to roughly three percent of GWP in 2100 for the BAU case. Deploying the CO_2 abatement strategy reduces the economic damages of climate change in the model to roughly one percent of GWP in 2100. The geoengineering strategy can reduce these damages even further down to less than one percent of GWP (in case of a continuous forcing) or it can increase the economic damages to roughly six percent (in case of an intermittent geoengineering forcing). It is important to recall that the damage function (i) does not consider damages due to changes in atmospheric CO_2 concentrations alone and (ii) that the calculations so far neglect damages due to the aerosol geoengineering forcing. Based on the considered strategies, environmental damages, and the adopted value judgments in the optimal growth model, the substitution of geoengineering for CO_2 abatement might reduce the environmental impacts of climate change or worsen them, depending on the probability of intermittent aerosol geoengineering.

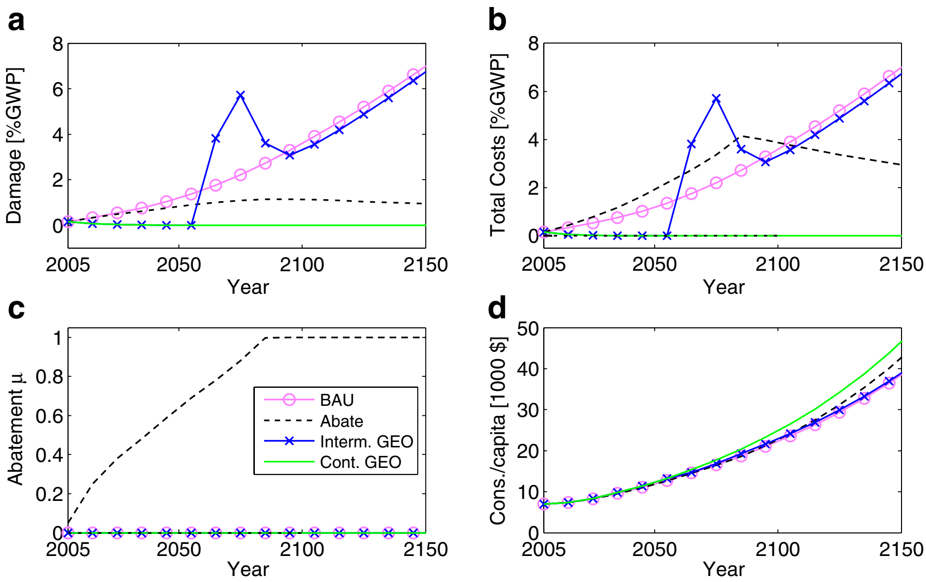

Fig. 4 Economic damage of climate change (panel **a**), total costs (i.e., CO_2 abatement costs and climate change damages cost), abatement, (panel **b**), fraction of CO_2 abatement (panel **c**), and per capita consumption (panel **d**) for BAU (*circles*), optimal abatement (*black dashed line*), intermittent geoengineering (*crosses*), and continuous geoengineering (*solid line*). Note that these results neglect potential economic damages due to aerosol geoengineering forcing

The total costs (i.e., the sum of economical damages and the costs of climate control driven by the CO_2 abatement) vary considerably across the considered strategies (Fig. 4b). For all strategies besides CO_2 abatement, the costs of controlling climate are zero, and only the damages drive the total costs. This is because abatement is zero for these strategies (Fig. 4c) and because the costs of aerosol geoengineering are assumed to be negligible following Barrett (2008) and Nordhaus (1992). For the CO_2 abatement strategy, abatement costs increase to roughly four percent of GWP around the year 2100 and decline afterwards due the parameterization of technological change in the model. For the intermittent geoengineering, the total costs are mostly higher than abatement after the interruption of the geoengineering deployment.

4.3 Two simple cost-benefit tests

Would substituting aerosol geoengineering for CO_2 abatement have the potential to enable a Pareto improvement in a discounted-utility-maximizing economic optimal growth framework? To address this question, we analyze the utilities for the different strategies across the range of considered parametric uncertainties. We consider first the case where geoengineering causes economic damages just through the impacts on global mean temperatures (i.e., $\theta = 0$) (Figs. 5 and 6). This test is performed by simply comparing the properties of the distributions of utility across all SOWs for the different strategies. In a second step, we analyze the combined effects of geoengineering damages due to changes in global mean temperature and due to the

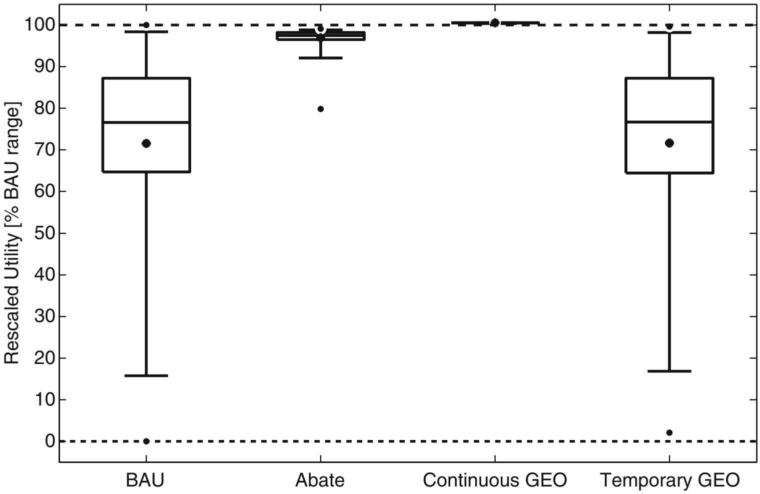

Fig. 5 Distribution of the rescaled objective function of the different strategies. Note that these results neglect potential economic damages due to aerosol geoengineering forcing

effects of aerosol forcing (Fig. 7). In this test, we compare the average utility across all SOWs of the abatement strategy with those of all geoengineering cases.

4.3.1 Effects of a potential intermittent aerosol geoengineering

The parametric uncertainty about climate sensitivity, abatement costs, and the economic damage due to temperature variations introduces introduces a considerable

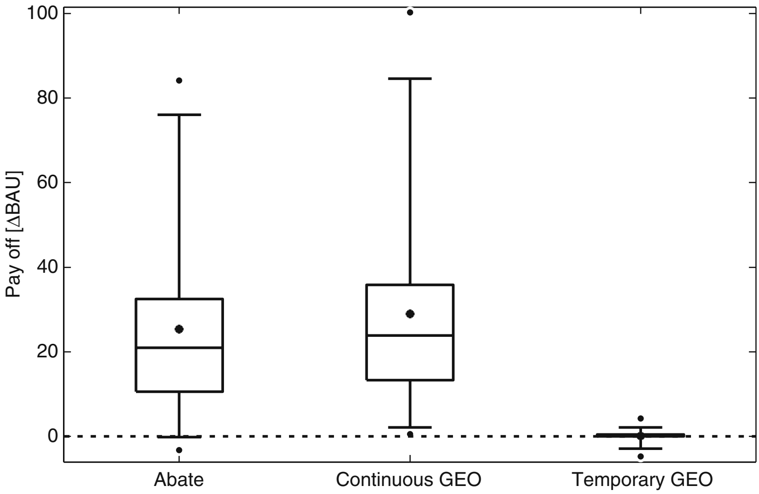

Fig. 6 Difference in the utility function (Eq. 1) across the uncertain states of the word relative to the business-as-usual strategy for optimal abatement, continuous geoengineering, and intermittent geoengineering. Note that these results neglect potential economic damages due to aerosol geoengineering forcing

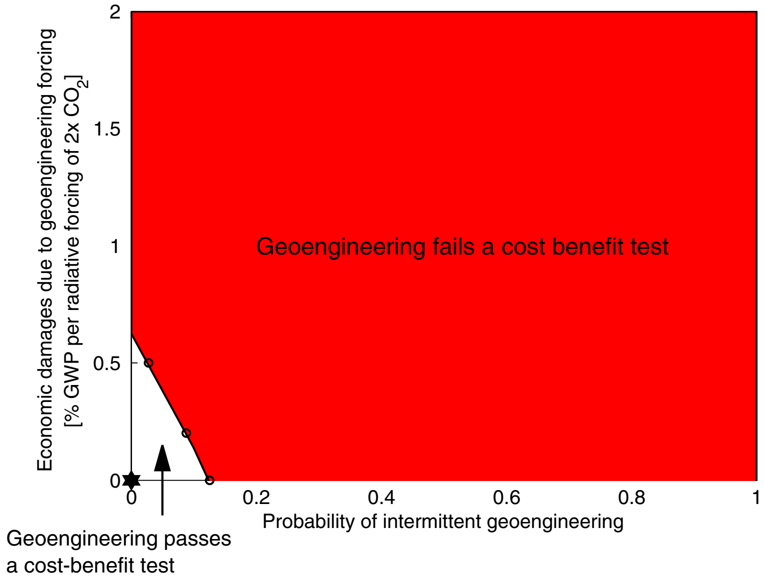

Fig. 7 Scenario map for the cost-benefit test to substitute aerosol geoengineering for CO_2 abatement as a function of the probability of intermittent geoengineering and the estimated damages due to geoengineering radiative forcing. The star at the axis origin represents the (sometimes implicit) assumption of many previous studies that both the probability of intermittent aerosol geoengineering is zero as well as that damages due to the aerosol geoengineering forcing are zero

variance in the utilities for the different strategies (Fig. 5). We analyze the objective function values of the different strategies (Eq. 1) re-scaled such that the utilities for the business-as-usual scenario cover a range of zero to 100 percent. The expected value (the star in the box-whisker diagram) is highest for the case when aerosol geoengineering is continuous, followed, in decreasing order, by the CO_2 abatement strategy, the business-as-usual strategy, and the discontinuous geoengineering strategy.

Some decision-makers might choose to maximize the rejoice (or minimize the regrets) of a decision compared to a base-case scenario (e.g., a business-as-usual strategy) (Savage 1954). Choosing abatement over the business-as-usual strategy leads to rejoice in roughly 95 percent of all considered cases (Fig. 6). Choosing the geoengineering strategy relative to the business-as-usual strategy leads to higher rejoice if geoengineering is continuous, but it leads to stronger regrets if geoengineering is intermittent. Note that substituting aerosol geoengineering for CO_2 abatement increases the variance of the regrets.

4.3.2 Implication of aerosol-forcing-dependent damages

The analysis, so far, assumes that geoengineering causes environmental damages only through the effects on global mean temperatures (i.e., for $\theta = 0$). As discussed above, the aerosol geoengineering forcing is projected to change Earth system properties such as precipitation- and surface temperature-patterns, El Niño, and polar ozone concentrations, to name just a few (Robock 2008; Lunt et al. 2008). A review of the current literature on the impacts of stratospheric aerosol on natural and human systems suggests that aerosol injections into the atmosphere might cause potentially sizable damages (Lunt et al. 2008; Robock 2008; Robock et al. 2008; Trenberth and Dai 2007). We characterize the economic implications of this deep uncertainty using a scenario map where we plot the regions where substitution of aerosol geoengineering for CO_2 abatement either passes (white region) or fails (red region) an economic cost-benefit test (Fig. 7) as a function of two deeply uncertain parameters: (i) the probability that aerosol geoengineering is discontinued (cf. Fig. 3a) and (ii) the sensitivity of economic damages due to aerosol forcing (parameter θ in Eq. 15). The solid line separating the two regions represents the cases where the expected utilities of aerosol geoengineering and CO_2 abatement strategies are equal. As shown before (e.g., Figs. 5 and 6 as well as Nordhaus (1992)), substituting aerosol geoengineering for CO_2 abatement passes a cost-benefit test in this simple model if geoengineering is not discontinued and if aerosol forcing does not cause economic damages. The most optimistic assumption, in which geoengineering is not discontinued and causes no damages is represented by the star in the axis origin of Fig. 7. This most optimistic assumption approximates the assumptions of several previous studies (e.g., Nordhaus 1992; Wigley 2006).

The conclusion derived from this most optimistic assumption hinges, however, on deeply uncertain assumptions about the probability of an intermittent aerosol geoengineering and the damages due to aerosol forcing. One may argue that the capability of future generations to maintain aerosol geoengineering forcings for decadal to century time-scales is unpredictable. Victor et al. (2009) points out that "Universal agreement (on geoengineering) is very unlikely. Unilateral action would create a crisis of legitimacy that could make it especially difficult to manage geoengineering schemes once they are under way." As shown in Fig. 7, the transition to the region where substituting aerosol geoengineering for CO_2 abatement fails a cost-benefit test occurs in our analysis rather close to the most optimistic assumptions, and the geoengineering strategy fails a cost-benefit test for most of the explored parameter combinations.

4.3.3 Mixed abatement/geoengineering strategy

Our previous results show that aerosol geoengineering as a substitute for abatement can represent severe risks for the future generations. However, geoengineering has also been discussed as a complement for abatement, which constitutes the mixed abatement/geoengineering strategy (e.g., Wigley 2006).

We analyze this mixed strategy by jointly optimizing the abatement and geoengineering trajectories (Fig. 8). In other words, geoengineering is not treated as an exogenous variable as in the previous sections but is an endogenous decision variable. We keep the same treatment of uncertainties described in Section 2.6, of 6300 SOWs and perform a sensitivity study for the magnitude of the aerosol forcing dependent damages (θ) with values of zero, one, two, three, and five percent of GWP per aerosol forcing equivalent to a doubling of atmospheric CO_2 concentrations. We neglect the possibility of intermittent geoengineering, hence the estimates of geoengineering damages are incomplete and the analysis is biased towards artificially high geoengineering deployment.

For the case with $\theta = 0$ (solid line, Fig. 8), abatement is zero and geoengineering counteracts the CO_2 radiative forcing completely. For intermediate values of damages ($\theta = 1\%$, triangles; and $\theta = 2\%$, squares), geoengineering increases in a high rate for the next 50 years and stabilizes when abatement is maximal at 100

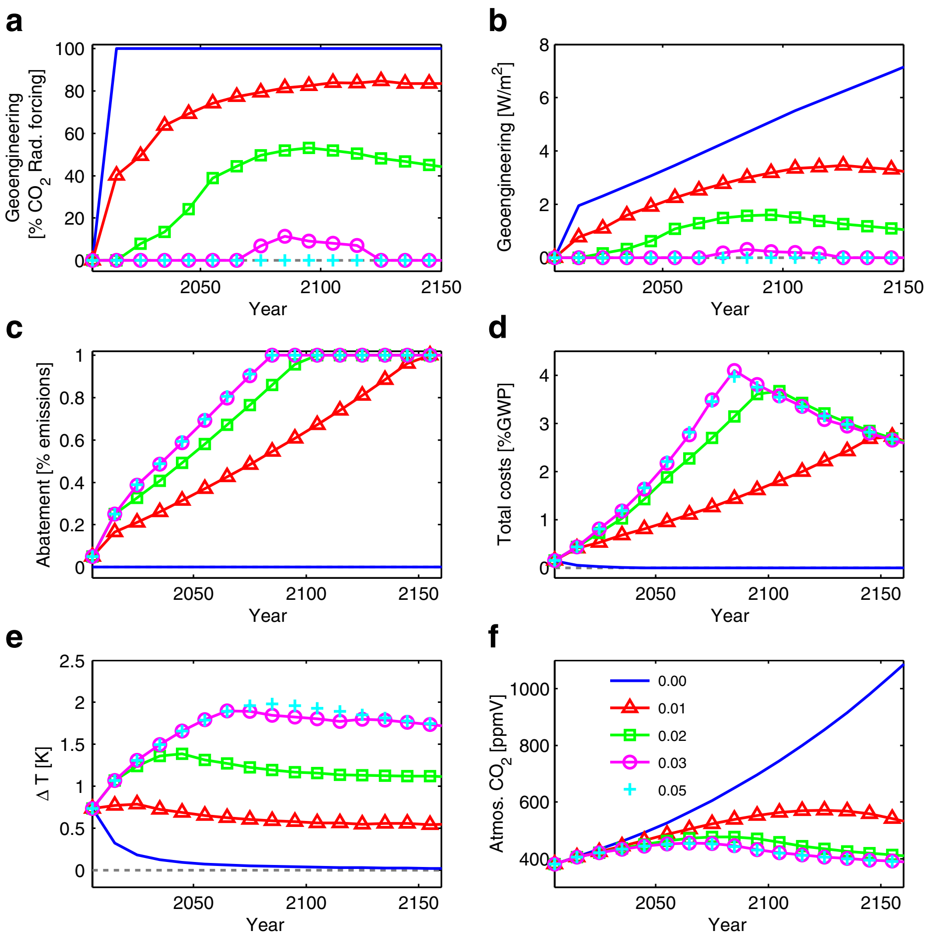

Fig. 8 Sensitivity of the geoengineering/CO_2 abatement portfolio (and related outcomes) to the damages due to aerosol radiative forcing: **a**) Geoengineering in percentage of CO_2 forcing, **b**) geoengineering radiative forcing, **c**) abatement, **d**) total costs, **e**) temperature change and **f**) global atmospheric CO_2 concentration of the mixed abatement/geoengineering strategy. Geoengineering forcing damages (θ) vary from zero (*solid line*), one (*triangle*), two (*square*), three (*circle*), and five (*cross*) percent of gross world product per forcing equivalent to a doubling CO_2 forcing. Figure 8b, d, e and f are the average over the considered states of the world

percent. For higher values of forcing damages ($\theta = 3\%$, circles; and $\theta = 5\%$ crosses), geoengineering is postponed for several decades, when the global mean temperatures and hence the marginal damages of anthropogenic radiative forcing are higher. In a sense, aerosol geoengineering is only used in the case of climate emergency.

5 Ethical implications

Economic analyses provide useful tools for policy decisions, but do not, by themselves, constrain action. The simple fact that some actions may cost more does not per se morally preclude the action. Economic analysis can inform ethical analysis but is not sufficient to derive principles for good action. Conversely, ethical analysis must be informed by relevant empirical data. As a result, analyzing the question whether aerosol geoengineering is ethically viable requires an analysis that integrates scientific, economic, and ethical analysis.

Policy decisions regarding climate change strategies thus require attention to issues of fairness and justice as well as to sound economic analysis. Our economic analysis of aerosol geoengineering is therefore coupled with considerations of what justice requires in order to inform policy. Two principles of justice directly relevant to policy formation regarding climate change strategies are distributive and intergenerational justice, which focus on fair distribution of harms and benefits between, in the former case, individuals or groups of individuals (distributive) and, in the latter case, present and future generations (intergenerational).

Our analysis is directly relevant to determining whether implementing aerosol geoengineering would satisfy principles of intergenerational justice. A widely accepted principle of intergenerational justice, originally introduced by John Rawls (1971, 2001) and further developed, for example, by de Shalit (1995) and Partridge (1981) maintains that each generation has the ethical obligation to insure that future generations have, at a minimum, "the conditions needed to establish and preserve a just basic structure over time" (Rawls 2001). A minimum requirement for satisfying these conditions is that future generations are guaranteed basic "welfare" rights such as food, clean water, safe shelter, and education (de Shalit 1995; Pogge 2002).

While there have been careful analyses of the significance of intergenerational justice in the wider context of climate change (e.g., Gardiner 2009; Page 2006; Wolf 2009), our study is the first to quantitatively examine issues of intergenerational justice raised by aerosol geoengineering. The analysis is particularly telling for a policy decision to deploy aerosol geoengineering and no or little CO_2 abatement. As we illustrate (Fig. 3) this strategy has vastly different impacts depending on whether the geoengineering is continuous or intermittent. In the latter case, discontinuation after a significant period of deployment (which we represented to be the year 2065, Fig. 3a), would result in a global mean temperature increase initially at a far higher rate, 1.5K/decade than that of a business-as-usual policy (Fig. 3d).

Our analysis provides data for better appreciation of the nature of the risks of a policy that would substitute aerosol geoengineering for CO_2 emissions abatement. Although such a policy would decrease the required abatement costs in the near term, it would impose sizeable risks for more distant generations. Our analysis illustrates that the economic damage caused by an intermittent aerosol geoengineering similar to the one we analyze would be as high as approximately six percent of gross world product (GWP) per year in the decades immediately after its discontinuation, after which the economic damage is identical to that of the BAU scenario, e.g. approximately three percent in 2100 and approximately six percent in 2150 (Fig. 4b). We thus show that discontinuous SAG results in far greater rates of temperature increase and economic damage than a business-as-usual scenario.

In quantifying the aggregate benefit and harms of an optimal abatement strategy, a business-as-usual strategy, and an aerosol geoengineering strategy, our analysis provides insights relevant to issues of intergenerational justice concerning the risks of a policy to deploy aerosol geoengineering with little or no abatement. In so quantifying the harms of intermittent aerosol geoengineering, we clarify the nature of the risk that would be transferred from current to future generations through such a policy decision. This information, combined with scientific understanding of the impacts of the abrupt warming due to a discontinuation of the aerosol forcing upon human communities and ecosystem integrity (Alley et al. 2002), clearly illustrate that this policy would put at risk the conditions required to satisfy basic welfare rights of future generations. Since intergenerational justice requires that current generations avoid policies that create benefits for themselves but impose burdens on future generations (de Shalit 1995; Pogge 2002; Rawls 2001), substituting aerosol geoengineering for CO_2 abatement arguably fails this basic principle of intergenerational justice given the potentially severe risks associated with a potential discontinuation of aerosol geoengineering (cf. Figs. 3–6).

Granting that many (e.g. Wigley 2006) advocate rather a mixed abatement/geoengineering strategy, we provide an analysis of such a strategy (Fig. 8), factoring in forcing damages, but ignoring the possibility of intermittent geoengineering to provide data for analyzing what would be an ethically responsible policy for such a strategy. Our analysis suggests that aerosol geoengineering may replace CO_2 abatement in an optimal portfolio, but only if the damages due to aerosol geoengineering are relatively small, a deeply uncertain assumption.

Although our analysis is silent on intragenerational distributive justice due to the globally aggregated nature of the economic model, we will take a moment to underscore why issues of distributive justice are an essential aspect of such a policy-decision. We raise these issues to stress the complexity of coupled economic-ethical analyses relevant to climate change strategies and to emphasize the need to develop more complex assessment tools (e.g., Tol 2008a) capable of quantifying such aspects. As noted above, the distribution of aerosol-forcing-dependent damages will not be equally distributed either spatially or temporally (cf. Irvine et al. 2010; Ricke et al. 2010). Changes in precipitation and surface temperature patterns will impact some regions more than others, and in those regions negatively impacted, the damages will be heavier on individuals and groups which are worst off in terms of income, education, or social status. While this feature of climate change strategies is not unique to decisions about aerosol geoengineering (see, e.g., Louis and Hess 2008; Schneider et al. 2007; Shue 2000; Vanderheiden 2008), nonetheless any efforts at quantification designed to inform just policy decisions must factor in such complexities. As just one example, consider estimates of the current mortality rates attributed to the recent climate change (Louis and Hess 2008). These (admittedly uncertain) estimates show higher climate change related mortality rates in low income regions such as Africa compared to higher income regions such as Western Europe or the U.S.A. As these examples illustrate, decisions regarding an aerosol geoengineering strategy raise issues of distributive as well as intergenerational justice. Hence, this study can be seen as a first step in a process of calling for more efforts to put economics to work in the service of ethics in the context of these highly complex impacts.

6 Caveats

Our model provides a simple and transparent analysis framework, which reveals heretofore overlooked aspects of decision choices regarding the potential deployment of aerosol geoengineering as a climate change strategy. While our analysis reduces some of the uncertainties of such a strategy, it is silent on a many potentially important aspects of the decision-problem. These model simplifications impose the following caveats on our forthcoming conclusions, while at the same time pointing to potentially fruitful future research.

First, our model neglects the potentially important effects of future learning about the system on the choice of risk management strategy (cf. Keller et al. 2004; Manne and Richels 1991). In a learning process, the new information typically reduces the parametric and predictive uncertainty (cf. Oppenheimer et al. 2008), i.e., the parameter probability density function contracts to a subspace. We hypothesize that the benefit cost ratio of aerosol geoengineering strategy is sensitive to the location of this subspace and increase, for example, with increasing values of climate sensitivity and the sensitivity of economic damages to climatic changes (cf. Alley et al. 2003; Keller et al. 2008b).

Second, our analysis considers only a small subset of the parametric and structural uncertainties. One such limitation, as noted in Section 5, is that the globally aggregated nature of our economic model precludes assessments of spatial distributions of harms and benefits needed to address broader and more complex issues of distributive justice. For example, an aggressive approach to aerosol geoengineering might serve the interests of low-lying islands (for example, to reduce sea-level rise), while exacerbating food security problems in some regions due to shifts in precipitation patterns. The analysis also assumes that the observed pattern of productivity growth (represented in the exogenous factor representing technology in Eq. 5) can be extrapolated into the future (cf. Nordhaus 2007), does not consider cases where the per-capita consumption would decrease for extended periods of time (cf. Tol and Yohe 2007).

Another example of the neglected structural uncertainties is the ethical framework of the economic model. The adopted economic model makes explicit value judgments and chooses a particular ethical framework (Nordhaus 2008). The most common systematic ethical frameworks within Western philosophy are: (i) consequentialist ethical theories which maintain that the ethical rightness or wrongness of an action is solely determined by the consequences of that action; (ii) duty based ethical theories in which duties rather than consequences are the basis of actions being ethically justifiable or unjustifiable; and (iii) virtue ethics which emphasizes the virtues and moral character rather than duties or the consequences of actions. Our economic analysis is based on a consequentialist discounted utilitarian framework. Alternative ethical frameworks and value judgments might require different approaches to represent issues of distributive and intergenerational justice (Tol 2001; Varian 1974) or the objective to reduce the probability to trigger "dangerous anthropogenic interference with the climate system" (Keller et al. 2000, 2005; UNFCCC 1992). We hypothesize that substituting one of these alternative ethical frameworks for the consequentialist discounted utilitarian perspective or an alternative value judgments (e.g., about the social rate of time preference within the consequentialist discounted utilitarian perspective) would change our results. This hypothesis is based on the considerable sensitivity of the results of past Integrated Assessment Modeling studies to such changes (cf. the discussion in Bradford (1999) as well as the results discussed in Nordhaus (1994b), McInerney and Keller (2008), Tol (2001), or Keller et al. (2007)).

Additional examples of neglected uncertainties include the fact that the damage function represents just a subset of the uncertainties of the experts, possible structural choices and parameterization of damages with respect to climate variables, and representation of ecosystem damages such as ocean acidification. Furthermore, we neglect likely important structural uncertainties involved in the projection of monetary discount rates (Newell and Pizer 2004). We identify these limitations not only for the purposes of accuracy, but also to draw attention to the need for more refined work in this area as a way to improve decision choices concerning just policy options.

Last, but not least, our study is silent on questions of distributive or procedural justice and the potential for moral hazards. A careful analysis of these important issues (cf. Bunzl 2008; Morrow et al. 2009; Schelling 1996; Schneider and Broecker 2007) is beyond the scope of this paper.

7 Conclusions

Given the aforementioned caveats, we draw from our analysis three main conclusions. First, aerosol geoengineering hinges on counterbalancing the forcing effects of greenhouse gas emissions (which decay over centuries) with the forcing effects of aerosol emissions (which decay within years). Aerosol geoengineering can hence lead to abrupt climate change if the aerosol forcing is not sustained. The possibility of an intermittent aerosol geoengineering forcing as well as negative impacts of the aerosol forcing itself may cause economic damages that far exceed the benefits. Aerosol geoengineering as a substitute for abatement can hence pose considerable risks to climate and economy. Second, substituting aerosol geoengineering for CO_2 abatement can fail an economic cost-benefit test in our model over a wide range of so far deeply uncertain parameter values (cf. Fig. 7). In contrast, (and as shown in numerous previous studies) fast and sizeable cuts in CO_2 emissions (far in excess of the currently implemented measures) pass a cost-benefit test. Third, aerosol geoengineering not carefully balanced by CO_2 abatement constitutes a conscious temporal risk transfer that arguably violates the principle of intergenerational justice. Fourth, whether geoengineering is deployed in an economically optimal portfolio hinges on currently deeply uncertain assumptions. Even if we assume that the probability of intermittent aerosol geoengineering is zero (an arguably very optimistic assumption), aerosol geoengineering is sometimes deployed only many decades in the future and is limited to small counter-forcing. The magnitude and timing of aerosol geoengineering in this case hinges on the so far deeply uncertain estimates of damages due to the aerosol forcing.

Our analysis has barely scratched the surface and is silent on many important aspects. More than a decade ago, a Unites States National Academies of Science committee assessing geoengineering strategies concluded that “Engineering countermeasures need to be evaluated but should not be implemented without broad understanding of the direct effects and the potential side effects, the ethical issues, and the risks” (COSEPUP 1992). Today, we are still lacking this broad understanding.

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