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An economic evaluation of solar radiation management

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ABSTRACT

Economic evaluations of solar radiation management (SRM) usually assume that the temperature will be stabilized, with no economic impacts of climate change, but with possible side-effects. We know from experiments with climate models, however, that unlike emission control the spatial and temporal distributions of temperature, precipitation and wind conditions will change. Hence, SRM may have economic consequences under a stabilization of global mean temperature even if side-effects other than those related to the climatic responses are disregarded. This paper addresses the economic impacts of implementing two SRM technologies; stratospheric sulfur injection and marine cloud brightening. By the use of a computable general equilibrium model, we estimate the economic impacts of climatic responses based on the results from two earth system models, MPI-ESM and NorESM. We find that under a moderately increasing greenhouse-gas concentration path, RCP4.5, the economic benefits of implementing climate engineering are small, and may become negative. Global GDP increases in three of the four experiments and all experiments include regions where the benefits from climate engineering are negative.

1. Introduction

Solar radiation management (SRM) belongs to a category of climate engineering with the possibility to mitigate an increasing global mean temperature at a negligible cost (Barrett, 2008). From an economic point of view, it thereby represents an opportunity which is difficult to ignore. A comparison of discounted costs and benefits gives an unequivocal answer at first sight: the benefits of bringing global warming to an end with climate engineering are clearly positive, while the benefits of even a slight emission control can be questioned (Nordhaus and Boyer, 2000; Bickel and Lane, 2009).

Although cost–benefit analysis is considered as a robust tool in most other contexts, there are few – if any – economists who support climate engineering for this reason. The main explanation is the risks involved. Most technologies are yet on paper with unknown effectiveness (Vaughan and Lenton, 2011), and the cost estimates of climate engineering technologies are mere suggestions (Klepper and Rickels, 2012). However, even extremely pessimistic estimates are far below the costs of emission control (Keith, 2000). This explains why the attention to risks in the few economic assessments of climate engineering is rather paid to the so-called side-effects, which can be divided into four categories. At first, we have the climatic side-effects. The technologies may succeed in keeping global mean temperature constant, but regional patterns and precipitation may change. Second, the non-climatic consequences of reduced radiation are more or less unknown. Third, the technologies themselves have side-effects which are unexplored, such as impacts of spraying sea-salt in clouds or injecting sulfur in the atmosphere over decades. Fourth, the side-effects may enforce an immediate shut-down of climate engineering, with unknown responses in the Earth system.

A few recent economic studies have addressed these side-effects. Gramstad and Tjøtta (2010) find that the high possibility of disastrous side-effects may turn emission control more attractive than climate engineering. Goes et al. (2011) show that possible impacts in the wake of an immediate shut-down favors emission control in most of the cases they have picked out. Bickel (2013) shows, on the other hand, that SRM may play an important role in dealing with the risks of climate impacts, such as tipping-points. The combination of low costs and quick response in the climate system may turn SRM into an attractive tool over an intermediate period.

The climatic responses to climate engineering are difficult to project. They will vary depending on the chosen technique, with different regional patterns that vary depending on which climate indicator we look at. The economic assessments of SRM that we have come across are all based on various versions of the DICE model (see e.g. Nordhaus, 2008), where impacts are fully determined by the change in global mean temperature. Studies of side-effects thereby cover an undefined cluster of at least the three first of the four categories distinguished above, represented by one or more probability distributions, which we

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hardly know anything about. Lessons from climate models, where regional and spatial distributions of temperatures and precipitation under stabilized global mean temperature are provided are thereby ignored.

This paper aims to bring economic assessments a step closer to the state of knowledge in climate modeling by making an economic assessment of the projected climate impacts of geoengineering from climate models. This paper estimates the economic impacts of stratospheric sulfur injection and marine cloud brightening. These are the two leading SRM techniques in the recent literature. The former draws on an analogy with major volcanic eruptions, which form a persistent layer of submicron sulfate particles about 20–25 km above the Earth's surface, reflecting solar radiation. Originally proposed by Budyko (1977), this technique has received renewed attention after the seminal paper by Crutzen (2006). Recent modeling studies indicate that the technique may in principle achieve a significant cooling of the Earth's climate (Rasch et al., 2008), but with a significant and poorly constrained risk of disruptions of the hydrological cycle (Haywood et al., 2013). Another undesired side effect to consider is stratospheric ozone depletion (Tilmes et al., 2008).

Marine cloud brightening, first proposed by Latham (1990), seeks to render layered low clouds over the oceans more reflective to solar radiation. This would be achieved by injection of sea salt particles that could in principle be extracted from the ocean surface (Salter et al., 2008). Global model studies indicate that a cooling effect sufficient to cancel a doubling of CO_2 concentrations might be achieved (Partanen et al., 2012; Alterskjær et al., 2012). However, model simulations at high spatial resolution indicate that the global models may be missing compensating effects associated with cloud dynamics (Wang et al., 2011) and precipitation (Jenkins et al., 2013). For both stratospheric sulfur injections and marine cloud brightening, the technical feasibility is unproven, and all the above simulations simply assume that the technique in question is feasible.

In this study, the economic impacts of sulfur injection and cloud brightening are estimated by the use of a global computable general equilibrium model, *Global Responses to Anthropogenic Changes in the Environment* (GRACE). The model addresses the economic consequences of impacts and adaptation to climate change, based on climate projections from two Earth system models, MPI-ESM and NorESM. The experiments use the emission paths of RCP4.5 (van Vuuren et al., 2011) as a base-line, and SRM is activated over the period 2020 to 2070 to keep the top of the atmospheric radiative forcing at 2020 levels. Thereby, global mean temperature is almost stabilized.

These scenarios are in line with the G3 scenario of the Geoengineering Model Intercomparison Projects (GeoMIP) (Kravitz et al., 2011). Climate effects of the transient scenarios have been discussed by Alterskjær et al. (2013) for the case of marine cloud brightening, simulated by the two ESMs used in this study. Niemeier et al. (2013) compare the effects of the two techniques simulated by the MPI-ESM. Multi-model studies of climate effects under the highly idealized GeoMIP scenarios have been described e.g. by Schmidt et al. (2012), Kravitz et al. (2013), and Tilmes et al. (2013), and with a specific focus on the termination effects caused by immediate discontinuation of SRM by Jones et al. (2013).

2. The economic model GRACE

Computable general equilibrium (CGE) models, such as GRACE, describe interactions between economic sectors and the final use of produced goods and services in a country or in world regions. They are based on national accounts data, and aim at projecting impacts on the national accounts data of given changes. The economic behavior of agents is based on maximization of profits in economic sectors, while consumers maximize utility of demanded goods and services. The model solves equilibrium prices and quantities where supply equals demand, under the assumption of free competition. This is why they are called general equilibrium models. In GRACE, general equilibrium is attained each and every year. The dynamics follows from exogenous assumptions related to the growth in population, which affects the supply of labor, rates of technological change, which gives the annual increase in output for a given set of input, and economic growth, which determines the stock of capital needed to attain the exogenously given output (gross domestic product or GDP) each year. To achieve this stock of capital, sufficient investments have to be made the previous year.

The production functions and utility functions in GRACE are all based on trees of dual Constant Elasticity of Substitution (CES) functions. Commodities and services are aggregated into groups which can be substituted pair-wise and form a new aggregate, which again may be substituted with another aggregate. For a further explanation of the structure of these functions, see Aaheim and Rive (2005). The demanded commodities and services in a region consist of a domestic part and an imported part, where the composite is determined by the relative prices between domestic and imported products, so-called Armington functions. GRACE specifies the trade of all goods between all regions.

World market equilibrium implies that the output from a sector in a region equals the world demand for this product. The income to sectors is spent partly on intermediate input factors and partly as remunerations to the primary input factors, labor (wages), capital (interest) and natural resources (rent). All remunerations are spent on final demand, either for consumption or for investments. Thus, financial markets are assumed to effectively allocate all savings into real investments, such that unemployment and financial crises do not appear in the model. Regional differences in the return on capital give rise to capital trade, and are leveled out over time according to an exogenously given rate. Natural resources are sector and regionally specific, while labor is mobile across sectors.

GRACE was developed to address the economic impacts of climate policy and climate change on the basis of climate projections from climate models, such as global circulation models (GCM) or earth system models (ESM). Projected average annual mean temperatures and annual precipitation over world regions are used as indicators for climate and climate change. These averages are taken from the grid points in the climate models over arable land to estimate effects in agriculture, over forested land to estimate effects in forests, and over populated land to estimate other effects. The calibration of effects of climate change refers to an increase in global mean temperature at + 2.5 °C. The full set of climate indicators used for this calibration is shown in Table A5 in Appendix A.

The version of GRACE used in this paper contains 15 economic sectors and divides the world into 11 regions, listed in Table 1. The model specifies sectors with large emissions of greenhouse gases and sectors where climate change may have a specific effect. There are five energy sectors and three transport sectors. Moreover, sectors based on the utilization of climate sensitive natural resources are specified. Regions are divided to cover areas with similar climate, although the size of the regions implies that there is a large variability within them. All regions are geographically coherent. The national accounts data and data for emissions are provided by GTAP (Badri and Walmsley, 2008).

The emissions of greenhouse gases in the current version of GRACE are confined to CO_2 from combustion of energy. The impacts of climate change are represented by the effects on the primary input factors and by changes in the demand for selected goods and services. Climate change thereby causes shifts in the supply and demand for goods and services. This brings about changes in market prices and quantities in all sectors in all regions. In this sense, the model addresses adaptation to climate change, sometimes referred to as autonomous and sometimes market driven adaptation.

The effects of climate change are represented by nine functions, shown in Table 2. The choice of functional forms is based on a European meta-study of all European countries (Aaheim et al., 2012). These were calibrated to fit the results of previous studies of the economic effects of changes in aggregated climate indicators over large world regions. The

Table 1
Sectors and regions in GRACE.

Sectors	Regions		
	Name	Abbr.	Comprises
Agriculture	Western Europe	WEU	EU15, Nordic, Iberia and Greece
Forestry	Central and Eastern Europe	CEE	Sovereign countries of the former Warsaw pact plus Baltic states and former Jugoslavia
Fisheries	Former Soviet Union	FSU	Other former Soviet states
Crude oil	Middle East & North Africa	MEA	Mediterranean Africa, and countries in the triangle Turkey – Saudi Arabia – Iran
Coal	Sub-Saharan Africa	AFR	States in Sahara and southern Africa
Refined oil	South Asia	SAS	Afghanistan, Pakistan, India, Nepal, Bangladesh, Nepal, Maldives, Bhutan
Electricity	East Asia	EAS	China, Mongolia, North Korea
Gas	Other Pacific Asia	PAS	Asian peninsula and island states
Iron and steel	Pacific OECD	PAO	Japan, South Korea, Australia, New Zealand
Non-metallic minerals	North America	NAM	USA and Canada
Other manufacturing	Latin America	LAM	Carribbean, Mexico and further south
Air transport			
Sea transport			
Other transport services			

estimated effects on arable land, on the growth of forests, of extreme events, sea-level rise and on health are based on four global studies, Mendelsohn et al. (2000), Nordhaus and Boyer (2000), Tol (2002) and World Bank (2008). The estimates for effects in agriculture were further refined by results in Cline (2007). The results from these studies were first adjusted to apply to the same increase in global mean temperature, at +2.5 °C. Then, the effects in the regions reported in each study were adapted to the regions in GRACE. As a general rule, the calibration is based on the resulting average effect from all the studies. In a few cases, adjustments were made to avoid unreasonable differences between regions.

Effects on fisheries, the electricity sector and tourism are even less studied on the aggregated level represented in GRACE than the abovementioned effects. The estimates in this study are based on single studies, and partly on assumptions. For fisheries, it is assumed that the stocks of fish in ocean fisheries are reduced by 2.5% while the productivity of sea in fish farming is reduced by 0.25%. Variations between regions occur partly because of differences in the contributions from fish farming, and partly because of different deviations from the "ideal" temperature. The electricity sector is affected partly by a need for cooling in thermal power plants and partly by the water supply in hydro power plants. The effects are thereby subject to the composite of plants within the electricity sector in the region. Estimates are based on Mendelsohn et al. (2000). The effects on tourism are estimated on the basis of Ehmer and Heymann (2008), which include estimates of the contribution of tourism to GDP, shown in Table A3 in Appendix A. 60% of the effect on tourism is allocated to the transport sector and 40% to the service sector.

An overview of the eight abovementioned effects at a +2.5 °C global warming is given in Table A2 in Appendix A. On average, the effects vary between −3.9% (tourism) and +4.6% (forests). The impacts on forests vary the most, from, −13% in Pacific OECD to +22% in Latin America. Still, the estimated effects assumed here are relatively moderate if compared with many other studies, as the use of averages means that no effect turns out as extreme. Because of the non-linearity of many effects, this may have large implications at higher temperature increases. All the parameters are shown in Table A5 in Appendix A.

Finally, the effects on the demand for energy are based on de Cian et al. (2007). The estimates for cold countries are used in regions with average annual temperature below +15 °C and for hot countries in regions with annual temperature above. Temperature adjustments of energy are, moreover, assumed to take place only in half of the year in all regions. The elasticities, which are shown in Table A4 in Appendix A, reflect a notable substitution effect, with a switch from coal to gas and refined oils at higher temperatures. Thus, cold days in cold regions increase the use of coal, while coal is not used for cooling purposes.

There are, of course a range of weaknesses in this way of assessing the effects of climate change with possible economic consequences. Firstly, the climate indicators are very rough, although more detailed than in most other integrated assessment models. Most other models refer to changes in temperature only, while GRACE includes effects of changes in precipitation. On the other hand, it is very difficult to single out effects of changes in precipitation from effects of changes in temperature in the source studies we have used. These studies have most likely estimated the effects of combinations of a specified change in temperature and an unspecified change in precipitation. Another refinement in GRACE when compared with other models is that we distinguish between climate changes over arable land, forested land and populated land, which are made possible by the use of projections from climate models instead of highly simplified climate modules used in most other integrated models.

Secondly, there is a vast uncertainty about the effects of climate change. Therefore, the resulting economic impacts should be interpreted more as "if so, then…" than attempts to come up with an estimate of what the economic impacts of a given climate projection will be. Our aim is to

Table 2
Impact functions in GRACE. T = temperature level in 2005, dT = change in temperature 2005 − t; dP = change in precipitation 2005 − t; Tfo = ideal temperature for forests, Tfi = ideal temperature for fisheries. a_i, b_i, c_i = parameters, π_j = shares.

Effect on	Affects	Symbol	Function
Productivity of arable land	Stock of natural resources in agriculture	$dR_a/R_a=$	$a_a dT^2 + b_a T dT + c_a dP$
Biological growth in forests	Stock of natural resources in forestry	$dR_{fo}/R_{fo}=$	$b_f[(T - Tfo) - (T - Tfo + dT)]^2 + c_f dP$
Stock of fish	Stock of natural resources in fisheries	$dR_{fi}/R_{fi}=$	$(\pi_f \Delta b_{1fi}[(T - Tfi) - (T - Tfi + dT)] + (1 - \pi_f)\,\Delta b_{2fi}[(T - Tfi) - (T - Tfi + dT)])dT$
Natural cooling and run-off	Stock of natural resources in electricity supply	$dR_{\mathrm{el}}/R_{\mathrm{el}}$	$(1 - \pi_e) a_e dT^2 + \pi_e c_e dP$
Extreme events	Total stock of capital, all sectors	$dK/K=$	$a_x dT^{\gamma x}$
Sea level rise	Total stock of capital, all sectors	$dK/K=$	$a_{sl} dT^{\gamma sl}$
Health	Total labor supply, all sectors	$dN/N=$	$a_h dT^2 + c_h dP$
Energy demand	Demand for energy in households	$El.(dT)$	$\mathrm{dE_h/dT} * \mathrm{T/E_h}$
Tourism	Demand for transport ($i = 1$) and services ($i = 2$)	$dX_i/X_i=$	$\pi_{ti}(a_t dT^{\overline{2}} + b_t T dT + c_t dP)$

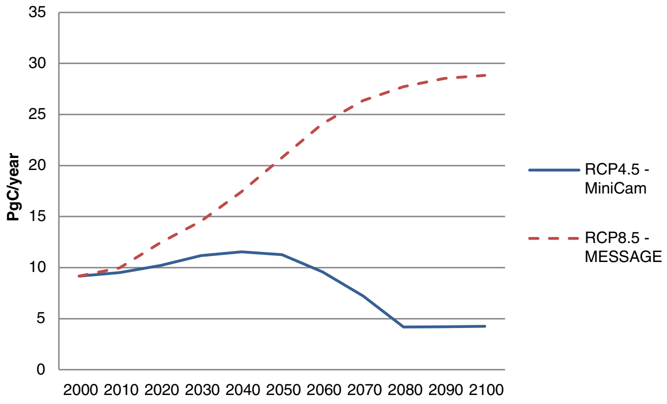

Fig. 1. Emission of CO_2 in RCP4.5 and RCP8.5. 2000–2100.

use estimates of the effects of climate change that can be interpreted as the present state of knowledge. There is also support for functional forms which give positive effects at a moderate temperature change, but negative at higher changes (e.g. Tol, 2010).

Thirdly, CGE models are based on a highly simplified description of an idealized world. Hence, the models are just reflections of the common approach to understand how economies work under these idealized conditions, with a special attention to interactions between economic activities within and between world regions. We must bear in mind that the real world is different. Therefore, the aim of running the model is first and foremost to see where this understanding brings us, and perhaps make us see results that were not foreseen or expected. This is also our defense for including some effects, such as on stocks of fish, which cannot be based on available numerical assessments, though there is a fair chance that the effects may be notable.

3. Climatic responses to marine cloud brightening and stratospheric sulfur injections

The point of reference for the calculations of economic impacts of climate engineering in this study is RCP4.5, which is one of the four concentration pathways recommended by IPCC as an input to climate modeling (van Vuuren et al., 2011). Emissions of CO_2, which are shown in Fig. 1, increase slowly to 2050, and then fall rapidly until 2080, when emissions are stabilized at approximately half of the present level. RCP4.5 thus presumes rather strong future global efforts to reduce emissions of greenhouse gases, in particular over the period 2050 to 2100. This becomes apparent if compared with the CO_2-emissions of RCP8.5, which can be considered a business-as-usual pathway where no mitigation takes place. The economic growth path in our study is based on RCP8.5. A charge on emissions is then imposed to approach the CO_2 emissions in RCP4.5. The carbon price in 2015 is 3.15 US$/tC, and twice as much in 2020. From then, it increases by 7 to 8% per year to nearly 70 US$/tC in 2050. Then, global emissions of CO_2 have to be reduced to follow RCP4.5, and the carbon price increases by more than 15% per year the coming decade, and around 10% per year until 2080, when emissions are stabilized at around 50% of the level in 2005. The carbon price in 2080 is 2065 US$/tC. To keep emission stabilized from then on, the carbon price increases approximately 0.5% per year in the period 2080–2100, when the price is 2325 US$/tC.

The climate projections were provided by two models, MPI-ESM in its LR configuration (Giorgetta et al., 2013) run by Max Planck Institute for Meteorology (MPI-M) and the NorESM, version ESM1-M (Bentsen et al., 2013), run by University of Oslo. The models are structurally different, and differences in climatic projections can therefore be expected. For each of the eleven world regions represented in GRACE, the regional trends in annual mean temperatures and precipitation were calculated. To account for the spatial distribution of climate changes within each region the values in each grid cell were weighted according to the cell's

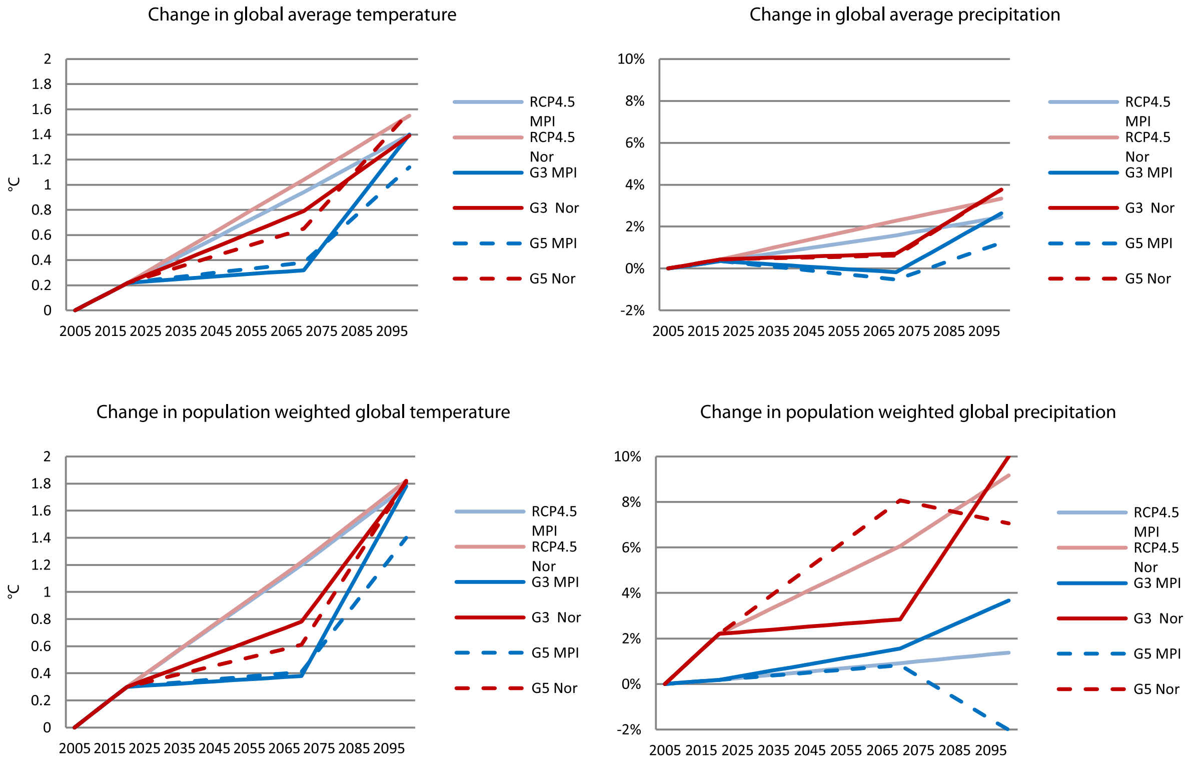

Fig. 2. Changes in global average temperature and precipitation (top) and population weighted temperature and precipitation (bottom) for RCP4.5, sulfur injection (G3) and cloud brightening (G5).

relative share of crop land, forested land and population within the region. Crop-land weighted changes in temperature and precipitation were used to estimate the impacts to the agricultural sector, forest-weighted changes were used for impacts to forestry, while the population weighted climate indicators were used to estimate all other impacts.

According to these runs, RCP4.5 results in an increase in global mean temperature between 1.5 and 2.5 °C from 2006 to 2100, depending on the weighting factor. The lowest increase in temperature is found in Pacific Asia, while America and Former Soviet Union have the highest temperature increases. Temperature increase is slightly higher over crop land and forested land than over populated land in most regions. Both models predict an increase around 3% in global mean precipitation from 2006 to 2100, but for the weighted results the models predict very different patterns. The increase in global population-weighted precipitation in MPI-ESM is only about 1.5% while the same value for the NorESM is almost 9%.

The difference between the projections in the two models can largely be attributed to different precipitation patterns over South Asia. The NorESM model predicts an 18% increase in population weighted precipitation over this region, while the MPI-ESM predicts a 2% decrease. Also for a number of the other regions it is difficult to trace a clear pattern for precipitation as the two models often give relatively weak and sometimes opposing trends. The exceptions are North America and Former Soviet Union, where both models predict similar increases of 4% to 7%, East Asia where the models predict an increase between 5% and 12% and North Africa/Middle East where models predict a reduction of between 7% and 12%.

The uncertainties concerning regional precipitation responses were also reflected in the responses of the CMIP5 (Coupled Model Intercomparison Project phase 5) model ensemble as presented by Knutti and Sedláček (2012) for the RCP8.5 experiment. In some densely populated regions like South and South East Asia and North America, agreement between simulated seasonal precipitation responses is low. By contrast, agreement on the temperature increase is in general high.

Both models also calculated the climate impacts of two different SRM technologies; stratospheric sulfur injection (implemented in experiment G3) and marine cloud brightening (implemented in experiment G5). The technologies were implemented in 2020 to keep the global mean anthropogenic radiative forcing constant until 2070. Then, the technologies were discarded abruptly and the climate models were run for 20 more years (until 2090). A standard CGE model with large regions, such as GRACE, does not capture the essential economic impacts of abrupt changes of a strong variability. To facilitate the economic interpretations, we have therefore calculated linear trends in the climate indicators over different periods instead of using the modeled annual mean values from the climate models. For the RCP4.5 scenario, trends for temperature and precipitation were calculated from the 2006–2100 annual means in each region. For the SRM scenarios, three time periods were used. In the pre-SRM period (2006–2019) the RCP4.5 trends were followed, then separate trends were calculated for each region in the SRM period (2020–2069) and in the post-SRM period (2070–2090 and extrapolated until 2100). Since trends are used, rapid changes in climate variables are smoothed out and the study makes no attempt to estimate the possible extra costs of such events, which has been a major topic for other economic studies, such as Goes et al. (2011).

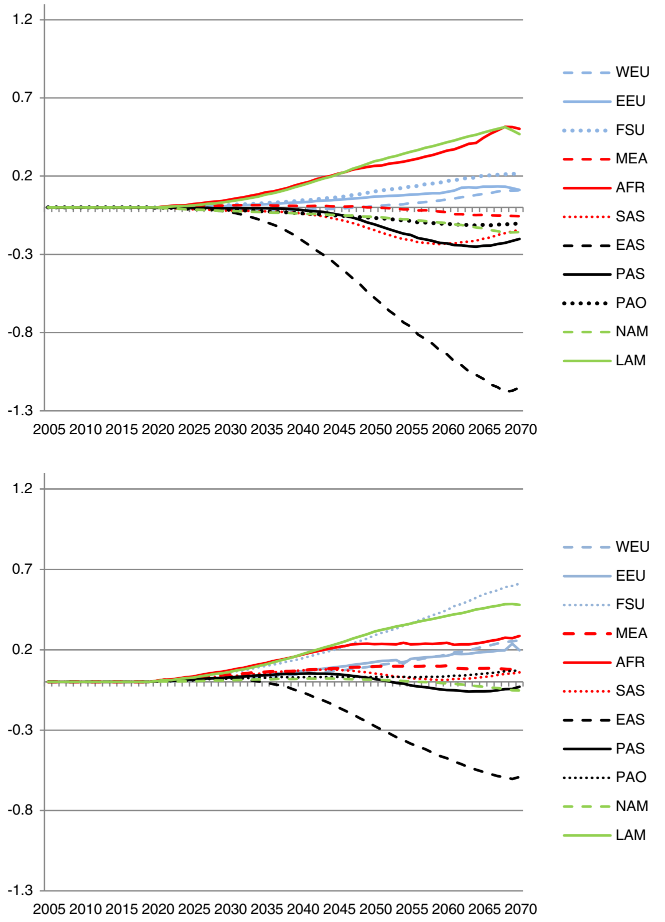

Fig. 4. Impact of stratospheric sulfur injection on GDP by region 2020–2070 in MPI-ESM (top) and NorESM (bottom).

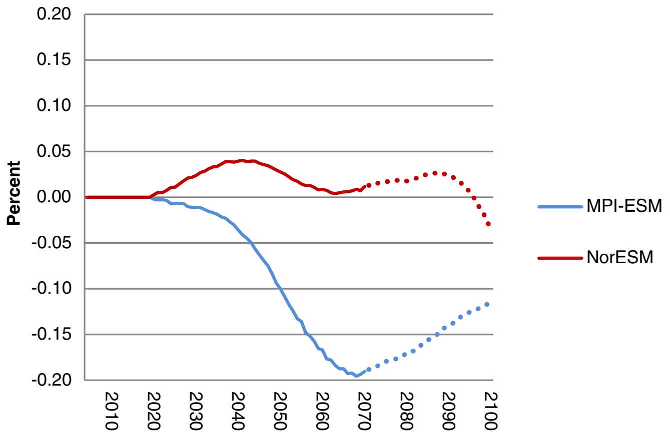

Fig. 3. Impact of stratospheric sulfur injection on world's GDP relative to GDP in RCP4.5.

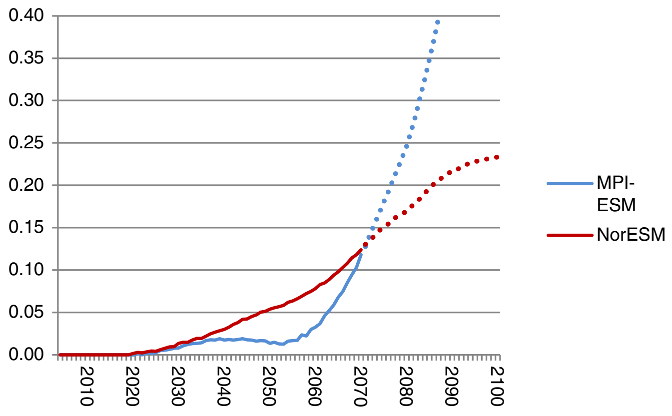

Fig. 5. Impact of marine cloud brightening on world's GDP relative to GDP in RCP4.5.

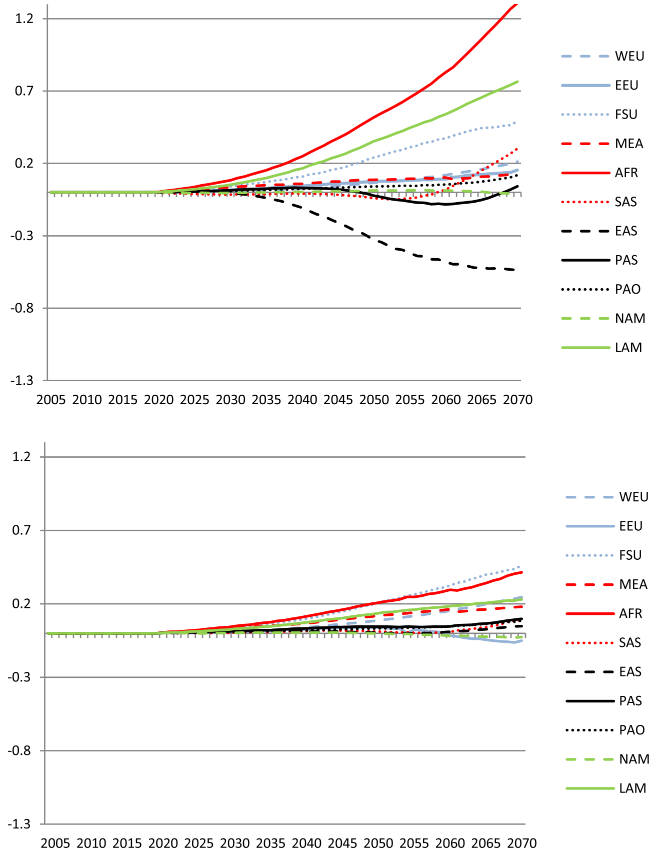

Fig. 6. Impact of marine cloud brightening on GDP by region 2020–2070 in MPI-ESM (top) and NorESM (bottom).

Fig. 2 shows the global mean temperature and precipitation trends as well as the global population-weighted trends for both RCP4.5 and for the two SRM experiments. We note that the difference in climatic responses between the two models is of similar magnitude as the climatic responses from the two SRM technologies projected by each model. MPI-ESM gives a stronger effect on temperature for both stratospheric sulfur injection and marine cloud brightening than NorESM. The difference is probably related to an imperfect cancelation of the increase in greenhouse gas forcing after 2020 through SRM. For the global average SRM implies a dryer climate in both models, but for the population weighted averages the technologies have opposite effects in the NorESM model while no clear pattern is evident in the MPI-ESM results. The global mean temperature over populated land in NorESM increases substantially also when SRM technologies are implemented, and the technologies seem to have a more effective response in MPI-ESM than in NorESM

It must be added that the regional distribution of changes in temperature and precipitation differs across regions. Except for Africa and South Asia, the temperature increases in all regions with both technologies in both models, up to nearly 1 °C in some regions in the NorESM. A weak temperature increase after year 2020 can be expected as the system is not in equilibrium in 2020. The residual pre-2020 forcing is not balanced by SRM and still causing warming. Both models give an increase in precipitation in Former Soviet Union, South Asia and North America and decrease in Latin America with both technologies. For the other regions, there are both positive and negative changes in precipitation, depending on technology and model. For a more detailed discussion of differences among the models for marine cloud brightening, see Alterskjær et al. (2013), and for differences related to the SRM methods in the MPI-ESM, see Niemeier et al. (2013).

4. Economic impacts

To comment on the economic impacts, we focus on the impacts on regional GDP, but add that alternative measures might be more appropriate, such as consumer surplus. These alternatives assume, however, that goods and services are optimally allocated over time. Since GRACE is not an intertemporal optimization model, we stick to GDP, which is also a common measure with all its weaknesses. The impacts also differ across sectors, but we concentrate on the aggregated effects here, mainly because of the space. A discussion of how sectors are affected differently by climate impacts in GRACE is provided in Aaheim et al. (in preparation).

The impacts on global GDP of the climatic responses to stratospheric sulfur injection in the two ESMs are shown in Fig. 3. Recall that the climatic indicators are taken from long-term trends and a potential abrupt climate change after SRM is terminated in 2070 is not included (thus the dotted lines). As opposed to previous economic evaluations, we find that one may question whether or not SRM yields a net economic benefit in the cases studied here. If based on the climate responses in MPI-ESM, global GDP will actually be reduced if sulfur is injected in the atmosphere to stabilize global mean temperature. The reasons are that there are economic benefits at a moderate temperature increase in several sectors and in several regions in the model, and that sulfur injection has unfavorable effects on precipitation in some regions. Since the temperature increase is most effectively mitigated by sulfur injection in MPI-ESM the potential benefits of a moderate increase in global temperature gained in RCP4.5 vanish. In RCP4.5 these benefits start to increase in 2050 and peak around 2070. During this period, the relative loss of sulfur injection increases according to the MPI-ESM path in Fig. 3. Note, however, that the overall economic costs are very small, and less than 0.2% of global GDP.

Sulfur injection in NorESM has a slightly positive impact on the global GDP. As shown in Fig. 2, the temperature response of sulfur injection in NorESM is less than half of that in MPI-ESM. Thus, more of the benefits of a slight increase of temperature are gained in the NorESM experiment. Further differences can be traced to regional distributions and changes in precipitation. A second reason is that the benefits of higher temperatures in the reference case of RCP4.5 are lower when we use the NorESM results than in MPI-ESM. In both cases, impacts are very small.

Our results thus indicate that sulfur injection cannot be motivated by the impacts of climate change under RCP4.5 on the value added of the global economy. On the other hand, these motivations are not mainly related to the global economy, but rather to national and regional interests. Because of the low costs, it may be implemented as one-sided actions by single parties without a global coordination (see the discussions e.g. in Millard-Ball, 2012). Hence, the regional distribution of impacts is probably a better indicator of the motivation for initiating SRM than impact on the global aggregate. Fig. 4 shows the impact of sulfur injection on GDP from the two climate models for the 11 regions in the GRACE model over the period 2010–2070, when the injection of sulfur is ended.

Again, stronger effects are resulting from the MPI-ESM model projections than from NorESM, which are due to the stronger regional climate signals. Moreover, while most of the regions in the NorESM projections benefit from sulfur injection, it leads to a loss in more than half of the regions in the projections from MPI-ESM. Many losing regions are large economies, which explain the relatively clear loss to the world economy in this case.

While the level and the number of regions that gain or lose differ between projections by the two models, there are clear similarities in the distribution of gains across regions. According to the climatic responses in both models, GDP in East Asia, where China dominates, declines with sulfur injection. This cannot easily be read from the climate signals. It is rather a result of the economic impacts of less warming, as agriculture in East Asia benefits more than most other regions from a moderate increase in mean temperature, and favorable trade effects. On the other side, Former Soviet Union, Latin America and Sub-Saharan Africa gain, in particular in the MPI-ESM projections.

The impacts on the world GDP from marine cloud brightening are shown in Fig. 5. The climate responses in both models give a small positive impact of about 0.1% in 2070, when SRM is shut down. The positive impact continues to increase after the SRM period. The explanation is that cloud brightening gives positive economic impacts due to the changes in regional patterns in temperature and precipitation until 2070, while leading to a general positive impact of a moderate increase in temperature between 2070 and 2100. Recall, however, that possible negative impacts of a rapid temperature increase are ignored in this study. While the annual improvement from NorESM is about the same each year over the entire period 2020–2070, the main improvement from MPI-ESM occurs after 2055–2060. The main explanations can be found in the regional responses.

The impacts on GDP by region are shown in Fig. 6. While the responses from NorESM may be characterized as very small also when considering the regions, the impacts from MPI-ESM range from relatively large positive to relatively large negative impacts. The shift in the growth rate from MPI-ESM on the world scale appears, moreover, to be a result of a slightly upward shift of trend for many regions in the period 2050–2060. From the NorESM projections, nearly all regions benefit slightly from marine cloud brightening, with a range between −0.05% and 0.4% in 2070 in Eastern Europe and Former Soviet Union, respectively. The corresponding range from the MPI-ESM projections is −0.5% in East Asia and +1.3% in Sub-Saharan Africa.

The regional distribution of economic impacts in the marine cloud brightening experiment does not display the same clear similarity between the two models that were observed in the sulfur injection experiment. Still, East Asia, which is among those regions that benefits the least in NorESM is the region that loses the most according to the MPI-ESM projections. Moreover, Sub-Saharan Africa and Latin America benefit more than most other regions in both models. However, the regional distribution of impacts of marine cloud brightening from MPI-ESM is, again, very similar to the regional distribution of impacts of sulfur injection in both models: On the top, we find Sub-Saharan Africa, Latin America and Former Soviet Union. East Asia is again the region with the largest reductions of GDP. Moreover, what distinguishes the sulfur projections in both models and the marine cloud brightening projections in MPI-ESM from the projections of marine cloud brightening in NorESM is first and foremost the range of impacts across regions, which is very small in the latter. Therefore, it is also difficult to point out what exactly distinguishes the impacts between regions.

5. Conclusions and discussion

Earlier economic evaluations of SRM techniques derive the economic impacts of climate change to the change in global mean temperature. Side-effects of SRM related to changes in the regional distribution of temperature and precipitation patterns, which can be identified by linking the economic impacts closer to projections from climate models, are thereby ignored. This study addresses these side-effects by estimating the economic impacts of climate change in eleven world regions. The estimates are based on projections of climate responses to sulfur injection and cloud brightening over the period 2020 to 2070 by the MPI-ESM and NorESM models, where emissions correspond to those of RCP4.5. In each region, the climate projections of annual temperature and precipitation over arable land are used to estimate effects on agriculture. Projections over forested land are used to assess effects in forestry, while all other effects are estimated on the basis of projections over populated land.

We find that economic benefits of SRM under a moderate emission pathway, such as RCP4.5, can be questioned. The total GDP for the world is higher than the reference case of RCP4.5 in both experiments with marine cloud brightening and in the NorESM projection with sulfur injection, while it is lower when the climate responds to the MPI-ESM projections of sulfur injection. In all four experiments, there are regions that lose from climate engineering, and the estimates made in this study give a strikingly similar pattern of the regions that gain in economic terms and the regions that lose. In particular, the economic impacts of climate engineering are clearly positive for Sub-Saharan Africa, Latin America and Former Soviet Union, while the loss to East Asia is relatively large in three of the experiments, and with no notable impact in the fourth, when marine cloud brightening is implemented in NorESM.

The results give substantially different economic impacts, both when comparing techniques and when comparing models. It is difficult to tell in general whether or not the results are more sensitive to the choice of model than to the choice of technique. Worth to note is, however, that cloud brightening in NorESM gives small economic impacts in all regions when compared with the three other experiments. An explanation is probably a significant positive response on precipitation in the projections of the model in this experiment, while the precipitation causes slightly negative effects in the three other experiments.

Our main message is that the economic impacts of SRM are not well addressed by assuming merely that the techniques allow global mean temperature to be held constant without reducing emissions, as previous studies do. One may instead question the economic benefits if the side-effects on the climate are taken into account. In addition, other possible side-effects, which we know little or nothing about, add to the risks of climate engineering.

Still, our results cannot be interpreted as a possible reason to why the motivation to implement climate engineering will disappear. The study has followed the tradition of previous studies, where climate engineering scenarios are compared with a baseline scenario with moderately developing greenhouse gas emissions, RCP4.5. Today, RCP8.5 seems to be a more realistic baseline scenario if there is no success in reducing emissions significantly. In fact, global emissions of CO_2 over the period 2005 to 2013 have exceeded the CO_2 emissions assumed in RCP8.5 by approximately 2.5%. RCP4.5 thus assumes substantial efforts to control emissions of greenhouse gases during the period when SRM is active in our study. This would be in line with the argument of Moreno Cruz and Smulders (2010), that climate engineering should be considered as an amendment rather than an alternative to emission control, but rationality from an economic point of view does not seem to explain the development of climate policy world-wide.

This is illustrated by the development of the carbon price needed to follow the CO_2 emissions in RCP4.5 in this study, which increases by more than 30% per year in the period 2005 to 2020. The economic interpretation is that the return on cutting greenhouse gas emissions today is 30%, which is far above any reasonable discount rate. Still we are unable to approach even RCP8.5, meaning that extremely strong economic incentives to limit global warming are apparently insufficient to spur necessary global actions. It is difficult to see major changes in this situation in foreseeable future. The climate will most likely continue to change, with gradually increasing impacts which some time in the future may become severe, even in macroeconomic terms. At that point, the motivations to keep climate change under control may change focus from the concern for the costs of emission reductions to a concern for increasingly severe impacts. Then, climate engineering may stand out as the only alternative, which will be more risky the less we know about the consequences.

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Appendix A

Table A1
Climatic references for comparison of cost estimates. Temperature in °C, Precipitation in rates. T = temperature level; dT = temperature change; Tfo & Tfi = ideal temperature in forests and fisheries; dP = rate of change in annual precipitation; Subscripts: p = populated land; a = arable land; f = forested land.

Indicator	WEU	EEU	FSU	MEA	AFR	SAS	EAS	PAS	PAO	NAM	LAM
T_p	11.45	10.30	8.10	18.98	23.02	24.76	12.90	25.19	15.32	11.69	20.90
T_a	11.05	10.30	7.11	13.94	24.18	23.88	10.97	25.12	17.45	7.59	20.97
T_f	7.28	9.35	−0.04	16.99	22.89	20.97	9.98	24.13	22.51	1.57	22.93
dT_p	1.45	1.85	2.37	2.69	2.58	3.27	2.90	2.13	1.79	3.45	2.90
dT_a	2.65	1.96	2.49	2.96	2.30	3.13	2.88	2.46	1.54	3.95	2.88
dT_f	1.99	1.79	2.88	2.79	3.07	2.84	2.82	2.40	1.35	3.95	2.96
Tfo	10.00	12.00	10.00	18.00	24.00	22.00	13.00	23.00	19.00	15.00	22.00
Tfi	16.00	13.00	11.00	20.00	22.00	22.00	17.00	22.00	18.00	13.00	20.00
dP_p	−0.080	0.080	0.200	−0.280	0.000	−0.130	−0.010	−0.110	−0.130	0.000	0.040
dP_a	−0.110	−0.110	0.200	−0.240	−0.010	−0.100	−0.020	0.040	0.040	−0.020	0.060
dP_f	−0.060	0.080	0.160	−0.100	0.005	−0.040	0.030	0.070	0.260	0.070	−0.100

Table A2
Rates of change in primary input (see Table 2) and demand (tourism and health) at a +2.5 °C global warming by region used as a reference for calibration of effect functions.

Effect on	WEU	EEU	FSU	MEA	AFR	SAS	EAS	PAS	PAO	NAM	LAM
Agriculture	−0.001	0.078	0.081	0.000	−0.059	−0.048	0.017	−0.004	0.000	0.079	−0.077
Forestry	−0.033	0.135	0.127	0.066	0.118	−0.005	0.023	0.039	−0.140	−0.046	0.221
Fisheries	0.024	0.003	−0.001	−0.024	−0.046	−0.082	−0.003	−0.046	0.001	−0.055	−0.059
Electricity	0.015	0.058	0.058	−0.011	−0.057	−0.009	−0.138	−0.026	−0.030	0.062	−0.120
Tourism	0.025	−0.038	0.028	−0.075	−0.075	−0.075	−0.075	−0.060	−0.098	0.090	−0.075
Extremes	−0.022	−0.009	−0.031	−0.014	−0.006	−0.015	−0.009	−0.011	−0.013	−0.013	−0.002
Sea-level	−0.006	−0.005	−0.007	−0.004	−0.001	−0.004	−0.004	−0.003	−0.003	−0.001	−0.001
Health	−0.001	0.000	0.000	−0.005	−0.025	−0.011	−0.004	−0.007	0.000	0.000	−0.008

Table A3
Rates for contributions to GDP from tourism by region.

WEU	EEU	FSU	MEA	AFR	SAS	EAS	PAS	PAO	NAM	LAM
0.087	0.078	0.057	0.060	0.067	0.044	0.106	0.083	0.085	0.089	0.061

Table A4
Temperature elasticities in household and service sector. Rate of change per °C.

	WEU	EEU	FSU	MEA	AFR	SAS	EAS	PAS	PAO	NAM	LAM
Coal	0.129	0.194	0.247	0.119	0.033	0.031	0.108	0.055	0.245	0.231	0.127
Gas	−0.115	−0.120	−0.152	−0.046	−0.013	−0.012	−0.041	−0.021	−0.094	−0.132	−0.049
Electricity	−0.002	0.043	0.054	0.016	0.005	0.004	0.015	0.008	0.034	0.019	0.017
Ref. oils	−0.063	−0.062	−0.079	−0.024	−0.007	−0.006	−0.022	−0.011	−0.049	−0.070	−0.025

Table A5
Parameter estimates in effect functions in GRACE. a_j relates to the effect of change in temperature, b_j relates to the dependency on the level of temperature, c_j relates to the effect of change in precipitation. For further interpretation of parameters, see Table 2.

	WEU	EEU	FSU	MEA	AFR	SAS	EAS	PAS	PAO	NAM	LAM
Agriculture											
a_a	−0.0235	−0.0131	−0.0096	0.0000	0.0044	0.0046	−0.0040	0.0004	0.0003	−0.0373	0.0062
b_a	0.0074	0.0041	0.0030	0.0000	−0.0014	−0.0015	0.0012	−0.0001	−0.0001	0.0117	−0.0019
c_a	0.5625	0.3139	0.2293	0.0005	−0.1051	−0.1114	0.0952	−0.0102	−0.0083	0.8931	−0.1480
Forestry											
b_f	−0.0071	0.0030	0.0030	0.0030	0.0030	0.0001	0.0033	0.0030	−0.0064	0.0042	0.0030
c_f	0.0079	1.0356	0.4187	−0.1883	−25.031	0.0003	0.0072	−0.5702	0.0079	0.0090	4.0205
Fisheries											
π_{fi}	0.1500	0.0750	0.0750	0.0500	0.0250	0.0500	0.0500	0.0500	0.1000	0.1000	0.1250
b_{1fi}	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250
b_{2fi}	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
Electr. supply											
a_e	−0.0120	−0.0120	−0.0120	−0.0015	−0.0086	−0.0009	−0.0199	−0.0061	−0.0096	−0.0120	−0.0526
c_e	−1.1446	6.8495	1.5893	0.0163	0.0931	0.0100	0.2154	0.0665	0.1045	46.4944	0.5703
Tourism											
a_t	−0.0064	0.0097	−0.0073	0.0194	0.0194	0.0194	0.0194	0.0155	0.0252	−0.0233	0.0194
b_t	0.0016	−0.0054	0.0143	−0.0029	−0.0034	−0.0030	−0.0056	−0.0021	−0.0046	0.0083	−0.0039
c_t	−0.0801	0.2680	−0.7174	0.1430	0.1688	0.1497	0.2795	0.1025	0.2280	−0.4171	0.1938

Table A5 (*continued*)

	WEU	EEU	FSU	MEA	AFR	SAS	EAS	PAS	PAO	NAM	LAM
Extreme events											
a_x	−0.0105	−0.0027	−0.0055	−0.0019	−0.0007	−0.0014	−0.0011	−0.0024	−0.0040	−0.0011	−0.0004
γ_x	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000
Sea level rise											
a_{sl}	−0.0031	−0.0020	−0.0020	−0.0009	−0.0002	−0.0007	−0.0008	−0.0010	−0.0013	−0.0001	−0.0002
γ_{sl}	1.5000	1.5000	1.5000	1.5000	1.5000	1.5000	1.5000	1.5000	1.5000	1.5000	1.5000
Health											
a_h	−0.0004	−0.0001	0.0000	−0.0007	−0.0029	−0.0010	−0.0005	−0.0014	−0.0001	0.0000	−0.0012
c_h	−0.0009	0.0002	0.0000	0.0014	0.0062	0.0022	0.0010	0.0029	0.0003	0.0001	0.0027

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