Answer to Reviewer 1

June 6, 2019

A general remark:

The reviewer repeatedly suggested describing in greater detail issues which are already treated elsewhere in the literature (most notably concerning the design and shortcomings of the DICE model and impacts of climate change). While we do appreciate his effort to eliminate potential ambiguities or omissions, we also believe that a research paper should not contain too much repetition of existing literature, and therefore tried to address many of these requests by adding a suitable reference.

General Comment 2:

To indicate that we indeed deal only with SRM, we did:

- replace “Geoengineering” by “Solar Radiation Management” in the title DONE
- mention in the introduction that negative emissions are not included DONE
- mention in the discussion part that trade-off between negative emissions, adaptation and SRM might be interesting wo study (with a more detailed model) DONE

General Comment 3 + 4:

We included in the introduction a short paragraph with references concerning model limitations (in particular: damage function; abatement costs not including learning-by doing; single decision maker; no CDR), but stated that we still believe that DICE to be a useful testbed for exploratory studies, which should of course be expanded by follow-up studies with more detailed models.

We also expanded the part on model imitations in the discussion. In particular, we clarified better how the limitations of the energy sector in DICE impact our results and mentioned the omission of negative emission and adaptation. DONE

However, we did not repeat details of the DICE model, e.g. the construction of the damage function, since these can be found in the cited literature. We did add Nordhaus and Boyer 2000 to the references, because this paper gives a lot of detail on how the damage function is constructed.

General Comment 5:

It is hard to compare the uncertainties of SRM and (unmitigated) climate change, because especially the former ones are hardly quantified yet.

The most important pair of options which arises from our study is not “Geoenginereering vs unconstrained climate change” (at least we strongly hope this will not be the decision humanity will face at the end!) but “Abatement-only vs Abatement+SRM (and if so, how much SRM)”. So basically, we want to investigate whether we should add SRM to our action portfolio or relate on abatement only. And for this question, the uncertainties surrounding SRM are absolutely vital - and far less well studied than the likewise daunting uncertainties surrounding climate change.

By the way, volcanic eruptions provide only an incomplete analog to SRM because their effect is relatively short-term; and it is highly unlikely that SRM-only will keep the climate “more or less at its present state”, in particular as far as precipitation is concerned.

We added a reference to IPCC WG2 for an overview on climate damage (introduction) and briefly mention the issues of irreversibility and delayed damage (e.g. in case of ice melt). DONE

Specific Comment Title:

See General Comment 2

Specific Comment P.1 L.2:

- “lower” -> “to lower”: adjusted DONE
- “may”: note that this is about damages from SRM, not from climate change. And there is *huge* uncertainty about adverse economic effects of SRM, so “may” is quite appropriate... no change made.

Specific Comment P.1 L.3-5:

This is the abstract, and therefore should be concise. So it is not the place to list everything *not* taken into account in this study.

To clarify that the focus is on economics, we replaced “gains and damages” by “(economic) gains and damages”. DONE

Specific Comment P.1 L.6:

change “should therefore be taken” into “therefore merits being taken”: adjusted. DONE

Specific Comment P.1 L.6-7:

Yes, we agree that CRD should be mentioned, but not in the abstract. See general comment 3-4.

Specific Comment P.1 L.9 & 12-13:

The paper is not primarily about reaching temperature targets. The statement in line 9 is a descriptive one; it describes a result but we did not enforce any target into the simulation itself. So the suggestion to try several targets is not applicable.

The statement in line 12-13 merely illustrates that humanity is not on its way to reach any suggested temperature target through abatement, which might make additional measures like SRM attractive. It is outside the scope of this study to discuss the justification of 2K or 1.5K as target.

For what is included in the damage function: Please consult the cited literature, in particular Nordhaus.

Specific Comment P.1 L.14-16:

Omission of CDR is clarified in introduction (see general comment 3-4)

Specific Comment P.2 L.6:

Again, this study is not an assessment of the severity of climate change, so it is not the scope of this paper to list or discuss all climate impacts in the text (as mentioned, we added a reference to IPCC WG2 for an overview).

Here we change “associated damages” into “heating-induced damages”, to reduce ambiguity (since some damages associated with / sharing common cause with climate change, like precipitation changes and ocean acidification, are not directly caused by warming). DONE

Specific Comment P.2 L.7-10:

Please note that part of the questions raised are treated in the literature cited.

Concerning the expected reduction in global precipitation: I am aware of no SRM study in which tweaking injection parameters (e.g. latitude, height, season of injection) avoids precipitation decrease, and there are plausible physical mechanisms why such a decrease should take place. Concerning precipitation patterns, there is more uncertainty and I expect that this more sensitive to injection parameters than the sign of the global precipitation trend. This is why we used the weak formulation “may”: It is quite perceivable that these pattern change (thus an important risk), but model uncertainty and the fact that injection parameters are undecided make it hard to quantity these effects.

Concerning sea level rise, this is one (important) component of temperature-induced damages (see Nordhaus’ paper for details).

Specific Comment P.2 L.11:

The cost of abatement is highly uncertain, because effects such as innovation, learning-by-doing, and customer behaviour are hard to predict (to say the least).

As a very crude indicator, we consider the cost of installing enough solar panels to meet its current energy demands.

Solar cells cost around 1 \$/W of capacity; this rises to 4\$/W when taking into account installation costs (at household level; may be different for large, remote solar parks). The sun does not always shine; let us be pessimistic and assume that only 20% of the capacity is actually used. This leads to an effective price of 20\$/W of actual capacity. [Numbers from Cassedy and Grossmann; see below for precise reference.]

The current human energy consumption is roughly $1.1 \times 10^{17} Wh/yr$. Installing solar cells to meet this demand would cost $\frac{20\$}{W} \times \frac{1.1e^{17} Wh/yr}{(365 \times 24) h/yr} = 2.5 \times 10^{14}\$$ or about 6 times the world GDP. This is about 600 times as much as the yearly cost of SRM at an injection rate of 30Mt(S)/yr (typical SRM level in our Abatement+SRM scenario at standard model settings).

Obviously, this is a very crude indicator for abatement cost. Our measure does not include maintenance costs of the solar panels (which are currently about 20% of installation costs), nor the much larger costs of dealing with the intermittency of the energy supply (restructuring the energy grid, storage capacity...), or growing energy demand. On the other hand, it does not include the benefits of energy efficiency increase, cost reduction by technology improvement (currently about 20% cost reduction per doubling of installed capacity), reduced cost for carbon-based energy production, pre-existing renewable capacity, etc.

We include this estimate briefly for comparison. DONE

Specific Comment P.2 L.13:

This paper is about whether or not to use SRM, not primarily about ethics of CO2 abatement. SRM has moral issues, such as the question of whom to put in charge of it, which are novel compared to those associated with global warming and abatement.

Specific Comment P.2 L.13-14:

Concerning the study by Robock on SO2 settling: The study used rather modest injection rates (about an order of magnitude below what we are considering here) and mainly dealt with the effect of SO2 on plants. The conclusion was that likely, at these small injection rates, the damage to vegetation is small, but at least in some regions, damage could occur if injections were tenfold.

Despite having severe impacts especially in large industrial agglomerations, industrial SO2 injections are a relatively regional phenomenon, because they are injected at low levels and washed after about a weak. SO2 from SRM could affect the entire atmosphere. So Robock's study certainly does not prove that SO2 loads from SRM have little effect. While the currently available studies, some of which we cited, give reason for concern, they are not extensive enough to quantify these concerns. Please note that in the Summary and Discussion section, we advocate to investigate these effects with a high priority.

The health issues associated with global warming are assumed to be part of the damage function for warming, and therefore - implicitly - reduced if the warming is reduced. A full assessment of health effects of unmitigated vs geoengineered climate is beyond the scope of this paper.

See also other comments concerning aspects of the damage function.

Specific Comment P.2 L.15-17:

While I agree that it is unlikely that the cost burden - or technical feasibility issues - will cause a sudden discontinuation of geoengineering, termination shock is still a relevant concern. (Armed) conflict could be one cause. More importantly, it cannot be excluded that the damage associated with SRM is higher than believed (for example, it could be that after a few decades of deployment it turns out that the long-term-effect on the ozone layer is detrimental, to name just one possibility).

And it is important to make clear that sudden disruption for whatever reasons could be detrimental, and therefore if choosing for substantial SRM, we are committed to continue it or at most phase it out slowly.

As you can see in the result section (fig. 2b, 3c), injection rates indeed decline towards the end of the simulation in the Abate+SRM cases. This is qualitatively the effect you mention, namely using SRM as a transition technology until abatement (which in principle could include CDR) sufficiently reduces CO2 concentration. We now highlight this important point in section 3.1. DONE

Specific Comment P.2 L.18-19:

The main aim of the study is to investigate whether or not to add SRM to the policy portfolio in addition to the already well-studied abatement. Calling it a "comparison between SRM and abatement" would imply that these options are alternatives. But the main alternative is "Abatement+SRM" vs "Abatement only" (or for short: "SRM or not").

We reformulated the "should". DONE

Concerning the explanation of the tipping point: It is numerically very hard to include several tipping points at the same time. We will now also study one different tipping point (namely a positive albedo feedback causing intensification of warming[1]) for diversity. DONE

Specific Comment P.2 L.19-20:

"Inefficiency": There are studies (Kleinschmitt 2018) which suggest that the maximum achievable long-time cooling might be limited - which would imply that at least extreme scenarios like cooling "RCP8.5"-like temperatures to pre-industrial values are impossible. Inserted reference. DONE

"Damage": while obviously the damage of unmitigated climate change would likewise be huge, it is not totally inconceivable that SRM causes some (unforeseen) damage, like massive destruction of the ozone layer or something we simply failed to think of. This may be unlikely, but we cannot know for sure. The inventors of the steam engine didn't think of global warming, either... We added the word "*unforeseen* damage" to clarify this, plus a reference to Robock2009. DONE

Specific Comment P.2 L.20-21:

Reformulated "the optimal policy" into "the (economically) optimal policy" to clarify this. DONE

Specific Comment P.2 L.31:

DSICE was developed based on the 2007 version of DICE, and later on the DSICE framework was adjusted in line with DICE2013. Now clarified and reference added. DONE

The main objective of DSICE w.r.t DICE is indeed to add noise or tipping. This was a major piece of achievement.

In our study, as described later in the methods section, the stochastic elements are only the tipping point and SRM failure.

Specific Comment P.3 Table 1:

If one wants to give a detailed explanation of all variables, then the extra width will not be sufficient. Also, the symbols are explained in more detail in the methods sections. However, to ease orientation, we added references to the corresponding equations or sections (or, in one case, to the literature). DONE

Concerning a) The value is the radiative forcing for e-folding (not doubling) CO2; see eq. 1

Concerning e) Precipitation goes up with CO2 because temperature goes up. If you add CO2 but keep surface temperature constant, then precipitation actually goes down. p_C only describes the pure CO2 effect; the temperature effect is in p_T. See eq. (6).

Concerning f) Damage is unitless, as it is expressed as fraction of GDP (see eq. 7); the damage associated with quantity X is of the form $\psi_X X^2$. This explains the units.

Concerning g) P2, L11 gives the range of cost per ton of injected gas; we assumed an intermediate value of $7 * 10^9 \$/Mt$. The table gives the cost per ton sulphur. Since we assume the injected gas to be SO2, which has twice the molecular weight of elementary sulphur, costs per ton (S) are twice as high as per ton of injected gas. This was also explained in line 27-30 on p. 6.

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[1] described as tipping point due to methane release in the original response letter, but since it is reversible, this (stylised) tipping point is better interpreted in terms of a purely temperature-dependent albedo feedback

Concerning h) If you mean capital depreciation, this has nothing to do with the discount rate, but with the fact that capital (e.g. machines) looses value over time (e.g. by being worn-out our becoming outdated). This is explained in Nordhaus 1992 to which we now added a reference in the table.

Specific Comment P.4 L.2-8:

Indeed, tropospheric ozone is a relevant greenhouse gas and should be mentioned here. DONE

On the other hand, since ozone is a byproduct of chemical reaction with anthropogenic emissions (e.g. CH4, CO in presence of NOx), the argument that "other forcing" can partly be abated, also holds for O3. So the coarse estimate on P4, L 11 can still be used.

Reference: Myhre et al., 2013 (IPCC WG1, chapter 8; see p. 760ff; fig. 8.4 also shows that scenarios with high CO4 concentrations tend to have high tropospheric ozone, confirming that ambitious abatement leads to lower tropospheric ozone)

Specific Comment P.5 L.5:

replaced "industrial processes" by "fossil fuel combustion" DONE

Specific Comment P.5 L.6:

True, the model does not explicitly include the effect that a reduction in forest area reduces the CO2 sink stemming from Carbon fertilisation (while the direct loss of carbon, namely the loss of biomass and humus, is assumed to be included).

While this effect is surely relevant for detailed analysis of the carbon cycle, I am fairly sure that the effect is not bigger than, for example, the error bar on the total carbon fertilisation effect itself. Simulation the carbon cycle to such a degree of detail is beyond the scope of this exploratory study.

Specific Comment P.5 L.19-20:

No, this simply sets the initial conditions. While we are not doing so now, it is in principle possible to include CDR by having negative emission terms in equations 3b and 3c ($E < 0$).

Specific Comment P.6 L.11-13:

Yes, global warming increases global precipitation. However, the atmosphere not only warms due to heating from below, but also from absorbing long-wave radiation. This is explained in detail in the studies by Andrews 2010 and MacMartin and Kravitz 2016 (especially their fig. 2b) cited here.

If you suddenly increase CO2 (say, double it instantaneously), then you get a negative precipitation response at first (timescale of about a year) and only then, when the surface warming effect kicks in, precipitation increases. Likewise, when you both CO2 but keep surface temperature constant (say by SRM) then precipitation also decreases.

If you increase CO2 gradually and have no SRM (i.e. the current realistic conditions) then the warming effect is stronger than the direct CO2 effect, leading to net precip. increase when increasing CO2. We now pointed this out in the text. DONE

Specific Comment P.6 L.13-15:

This sentence (line 13) is about (direct) precipitation response, not temperature response. The explanation here was merged with the previous one (just prior to eq. 6) and slightly expanded, to generate more clarity. We also explained the meaning of $p_T T$, $p_C F_C$, $p_S F_S$ here. DONE.

Specific Comment P.6 L.16-17:

While non-linear effects might be present, MacMartin and Kravitz show that a linear emulator yields quite a reasonable approximation. So there is no use here to introduce additional complexity.

Specific Comment P.6 L.19-21:

Since we are taking over the damage function approach from DICE, we will not repeat its explanations here, but added the corresponding reference to Nordhaus' work.

Nordhaus tried to incorporate non-GDP aspects into his damage function (see also Nordhaus and Boyer 2000, now cited in the introduction and section 2.1.3), for example through his "willingness to pay" approach. The DICE damage function has been criticised extensively, and with good reason. However, creating a proper (or even acceptable) damage function is tremendously complex and still an ongoing field of research. So this is outside the scope of this exploratory study.

In your example, the loss of the town would count as a damage in Nordhaus' approach. Basically, the idea is that each period, humans produce "something" ($\bar{Y}$, the gross GDP) and part of it gets lost due to climate change. Non-material losses are converted into material loss.

Specific Comment P.6 L.22-24:

10% economic drop *forever* is quite significant (for comparison, the Great Depression around 1930 cut GDP by 15% for just a few years), and of the same magnitude of losses used in other studies, like Cai and Lenton 2016. Of course, you could come up with scenarios that are worse. However, doubling the tipping damage does hardly affect policy (see sensitivity run in table 4). A reason is that tipping usually occurs in the far future, which is strongly discounted. A second reason is that tipping is unlikely, if abatement and SRM are combined (i.e. it only occurs SRM failure).

In general one might question the DICE model's optimism about economic growth, and the way how discounting is used. This is outside the scope of this study.

Specific Comment P.6 L.26:

There would likely be initial development costs which don't increase with the amount of deployment.

However, the manufacturing of airplanes, fuel costs, costs for producing the injected gas, and manpower for operation all increase probably linear with injection rate. Given the large uncertainty (factor of about 5) in the cost estimates, we decided to stick to a simple, i.e. linear approach, and omitted initial costs, for which there is no good estimate.

Decreasing effectiveness of SRM is indeed treated separately, namely through the radiative forcing equation.

Specific Comment P.6 L.29-30:

It has been considered to use H2S. However, some raise concern that this gas is much more toxic than SO2. Also, we wanted to be conservative, and prefer to overestimate rather than underestimate the cost. This is now clarified in the text. DONE

Specific Comment P.7 fig1:

The pathway CO2-warming-more rain is represented by the two arrows with a plus sign going from CO2 to T and from T to P. The arrow from CO2 to P is only the direct effect. The direct effect is quite important in the context of SRM which can partly offset the pathway via warming. Although the temperature-mediated effect of CO2 on precipitation is dominant in case of slow CO2 increase and zero SRM, it needn't be dominant when SRM is involved. So trying to scale the arrows could be misleading (especially if you want to do it in a quantitative way, e.g. letting the arrow width scale with the strength of the effect represented, because the corresponding constants have different units).

However, we inserted a reference to eq. 6 in the figure caption, so that the interested reader can refer back to the (now improved) explanations. DONE

Specific Comment P.7 fig1 caption:

The mentioned damage from SRM is only the damage caused by SRM directly; reduction of damage from global warming is of course also modelled, but this goes via reducing the warming T. We inserted that SRM causes "*direct* damage of 20%" to clarify this. DONE

Specific Comment P.7 L.4:

Sea level rise is accounted for as part of the temperature effect.

Adaptation is not included (yes, one of the many shortcoming of the DICE model... now mentioned in the introduction).

Specific Comment P.7 L.5:

Atmospheric CO2 may not be damaging in itself, but we use C as a (rough) proxy for ocean acidification, which we do not model explicitly. This is now clarified. DONE

Specific Comment P.7 L.6-7:

The baseline for P is pre-industrial (as mentioned two lines above, L5).

The baseline for damage is also pre-industrial (in other words, if P, T, C would remain at pre-industrial levels, no "extra" damage from climate change occurs) which followed from the fact that $D = 0$ if $C = 0, T = 0, P = 0$.

I do not fully understand the last sentence. If the precipitation changes with SRM are smaller than without SRM, then the contribution of precipitation to the damage is smaller with SRM than without.

Specific Comment P.8 L.6:

The cost of sea level rise (which also makes storm surges more severe) is included in the temperature contribution of the damage (see Nordhaus and Boyer, 2000). That contribution goes quadratic with temperature, i.e. not linear (See eq. 8)

Specific Comment P.8 L.15:

See also previous comment on tipping.

The constraint is partly numerical. You could in principle allow multiple tipping points, for example one with higher likelihood and 10% loss, and one with lower likelihood and much higher loss. However, with dynamic programming, this will increase computational efforts very much, and given the relatively small impact of tipping on overall policy, we did not do this. (Cai et al, 2016 did, but they had only one decision variable, namely abatement.)

To add diversity to the representation of tipping points, we are now also investigating a different type of tipping point, in which global warming triggers a positive warming feedback (suggestion by reviewer 2) thought of as albedo feedback.

DONE, new sect. 2.4

Specific Comment P.8 L.18:

Some tipping points are considered possible at lower, some at higher thresholds than 2K. Since we have included only one stylised tipping point (see previous point), we chose a compromise. The value is inspired by the Paris agreement to keep (well) below 2K warming. We now performed a sensitivity run with 1K as threshold, but the effects on policy are minimal.

DONE

Specific Comment P.8 L.21-22:

The idea here was to investigate in a stylised, qualitative way the hypothetical possibility that SRM might in whatever way be "unreliable". Being conservative towards geoengineering, we preferred to overestimate this possibility rather than underplay it (since no good estimates are available anyway).

Disruption of geoengineering is not totally inconceivable (who knows, it *might* destroy the ozone layer, or it *might* be that a war destroys the SRM infrastructure).

Since the result is that SRM is used anyway, despite the rather large failure probability (see also section 3.4, sensitivity runs), choosing a smaller failure probability is unlikely to affect the overall results.

Specific Comment P.8 L.24-25:

The matter of the termination shock is briefly investigated in section 3.3. We now added a remark here to clarify that the matter will come up later. DONE

Specific Comment P.8 L.26-27:

DICE is a globally aggregate model. While it would be interesting - indeed, highly important - to study the effect of inequality, this is outside the scope of the current, exploratory, study.

Specific Comment P.9 L.1-6:

This is really getting repetitive.

I agree it is helpful to clarify in the beginning and / or discussion that our model is limited and our study therefore only an exploratory one, (as we did now in the introduction); but it makes no sense to discuss the same things over and over and over again throughout the text (or the review).

Discounting is a different phenomenon from the duration/reversibility of damage. The way to take into account the irreversibility of loosing the Amazon rain forest would not be to fumble around with two discount rates, but to change the damage function such that this contribution to the damage does not decrease again even if temperature deceases again. Note that our tipping point obeys this type of irreversibility dynamics - once tipped, the associated loss remains constant (even if temperature should decrease again), as pointed out in the beginning of section 2.1.4.

Specific Comment P.9 L.20-21:

Reformulated (following also a suggestion by reviewer 2) as: "Although the objective for the optimisation is the expectation value of the welfare, it is also interesting to investigate the range of possible welfare outcomes, especially the worst (or at least relatively bad) case scenario." DONE

Specific Comment P.9 L.29:

Yes, in the sense that it was used as benchmark (see also result section), e.g. to compute performance. Clarified. DONE

Specific Comment P.10 L.6:

The idea of this scenario is again to be conservative and check whether SRM might make sense even under unfavourable conditions - e.g. taking a long time to develop the technology. The scenario serves as comparison to the Abatement+SRM scenario where no such restrictions were present.

As a matter of fact, while obviously the parameters (time till SRM becomes available and likelihood of becoming available) are arbitrary and not constrained by data (so yes of course, one could have taken 2045 instead of 2055), I do not think they are particularly implausible. Properly assessing risks and efficiency, developing the technology, developing a legal framework for international collaboration, stopping security leaks, and convincing the general public that SRM is a good idea, are all difficult processes with an uncertain outcome. Nearly all big (government) projects take much longer than planned. Many pilot project of CDR/CCS have been stranded or at least greatly delayed due to public discontent, technical difficulties, economic problems, and so on.

In addition, it is unclear whether sufficient radiative forcing can be generated (see Kleinschmitt et al, 2018 cited in the introduction).

Clarified motivation for the scenario at the end of section 2.3. DONE

On irreversibility of damages, see remark p.9 L.1-6

Specific Comment P.10 L.14:

I doubt whether the term you mention is bigger than the extra energy demand to build and fuel the SRM airplane fleet... or the change in need for warming in winter... or the effect of temperature on plant respiration and the solubility of CO_2 in the ocean. Most of these terms are quite uncertain. Without denying that SRM could influence CO_2 emissions and uptake, it makes little sense to try and include them into such a simple, exploratory study, especially not if we cannot even be sure whether we get the overall sign right.

Also, which study do you refer to? If it is the report by IEA: I just heard a presentation by a student of Guus Velders, mentioning that the study has considerable flaws.

Specific Comment P.10 L.16:

We did not include running-out of fossil fuels to avoid computational complications.

While the reserves of gas, oil and coal that we are relatively sure to be mineable will last a limited amount of time (about 50, 50 and 100 years, respectively; estimates from 2010-2014), it is believed that there are vast amounts of additional resources (e.g. fracked gas which since then came more and more into use; and potentially clathrates for gas), and undiscovered coal reserves. Some estimates assume that at present consumption rates, coal might last for 1000 years. So our no-action scenario is maybe extreme, but not impossible.

Source: Cassedy, E.S. and P.Z. Grossman, "Introduction to Energy", third edition, Cambridge University Press, 2017; p31-32.

We acknowledged this in the manuscript. DONE.

Specific Comment P.10 L.19:

To cool the earth to pre-industrial from, say, RCP8.5 radiative forcing in 2100 would involve sulphur injections amounting to something like *14 Pinatubo eruptions* every year. Surely, that would be disruptive, too...

The sentence is simply a description of results using the current damage function. You can argue that maybe the damages for warming should be higher and for sulphur lower, especially for situations with high CO2 and high SRM. This would lead to more SRM and lower temperature in the SRM-only scenarios. But even then, you would very likely see that, since SRM is so inefficient at high forcings, it is a bad idea to lower extremely high temperatures back to pre-industrial with SRM alone. It is way better to use also abatement, or, if this were not done, you would still resort to reducing some, but not all, warming with SRM (also because admitting some warming will reduce the precipitation-related damage which would result from compensating all warming by SRM).

So the main conclusion to draw from the SRM-only scenario is that if you care about long-term effects, you'd better do abatement. We pointed this out more clearly. DONE.

Specific Comment P.11 fig.2:

The constraint of SRM starting not before 2055 only holds for the scenario dubbed "realistic storyline" (for which the results are only discussed later, see fig. 4), not in the stylised scenarios of fig. 2. This is outlined in section 2.3.

Concerning the time axis: We usually omitted the first time step, as it is a spin-up step. Now provided a consistent figure. DONE

Specific Comment P.12 tab.3:

Indeed, this is the value in the first time step - we now point this out in the caption of table 2 and 3. DONE

For remarks about reliability of SCC, see p14, L25ff.

For the calculation of abatement costs, see the cited literature on the DICE model. As we now briefly mention in the introduction, DICE assumes abatement always to be costly, although abatement costs go down in time. This is certainly questionable; but here we wanted to explore qualitatively what happens when SRM is added, and not rewrite the entire DICE model at once...

See also p.19 lines 1-3 for a short remark on the issue of learning by doing.

Specific Comment P.12 L.14-15:

See numerous previous comments concerning tipping points

Specific Comment P.13 fig. 3:

Is this actually a question? Concerning abatement and energy transition, see remark P.12, tab.3

Specific Comment P.14 L. 7:

This is the SRM-only scenario, for which we did *not* assume SRM to start only in 2055. See Methods section (sect. 2.3).

All we state here is that (in fig. 3b) the policy maker increases SRM when hitting the 2K threshold, in order to reduce the chance of tipping.

Specific Comment P.14 L. 16:

this seems not to be a question or suggestion...

Specific Comment P.15 fig. 4; P.16 L. 1:

See numerous previous comments on damage function and general DICE problems.

The conclusion from "realistic storyline scenario" vs. "Abatement+SRM" (which assumes immediate availability of SRM at 100% likelihood) is: As soon as SRM becomes available, if at all, it should be used to complement Abatement - unless termination shock damage and failure probability are really high.

This result would not change under a sensitivity study as suggested here.

Specific Comment P.16 L. 2-3; L. 5-6:

Clarified in Methods section on failure that it is indeed irrevocable. Also clarified there that failure is at present state speculative (though not impossible).

The sensitivity run on κ_{fail} showed that the main results are not very sensitive to the exact failing probability (if SRM is available, it is used even if it might fail somewhen).

Specific Comment P.16 L. 17:

I cannot see a connection between this remark and P16, L17, sorry.

abatement costs have been discussed already in previous comments....

Specific Comment P.16 L. 26:

Discussion on reliability of absolute CCS values: See p.14, l.25, including the reference to van den Bergh and Botzen cited there, which explains why CCS should be higher than DICE-like models.

Specific Comment P.16 L. 31-33:

Do we really need to estimate/conjecture/contextualise "huge" damages for an effect which we did *not* take into account? All we are saying here is that we *do not include scenarios* in which research on SRM (which would probably include testing at some stage) will cause huge/significant/whatever damages.

Of course, research cost on SRM is one of the myriad things one could investigate. But this would really blow up computational costs due to having another variable - especially if you want this to be an extra decision variable -, it would also introduce yet another layer of ill-constrained parameters (likelihood and size of damage during tests) and the effect on the results would likely be small. The possibility of "something going wrong early on with SRM" is qualitatively included by having a high failure probability in the first steps after SRM becomes available.

Specific Comment P.17, L1:

What DICE really needs is a proper energy sector, including effects like learning-by-doing, and that is outside the scope of this study.

We did, however, perform a sensitivity study where abatement costs remain exogenous, but decrease faster than in the standard settings, to investigate whether abatement costs have a large influence on policy (and thus whether this is an important aspect to study with better models). The result is that if abatement costs increase faster, more abatement and less SRM is used. So indeed abatement costs (and hence probably learning-by-doing) affect the need for SRM.

DONE.

Specific Comment P.17, L9:

If you do more abatement, you need less SRM.

CO2 has a long residence time; so abatement done now also affects future carbon levels and therefore reduces the need for SRM. SRM will always come at costs, so for a future generation it is always beneficial of they have to do less of it because a previous generation has done more abatement for them.

The lower ρ, the more prepared the earlier generations are to pay for abatement.

By "SRM causes damage" it is meant that SRM makes a contribution to damage, see ψ_S.

Specific Comment P.18, L3:

Nice suggestion. Result: SRM increases by ca 25%, but no qualitative change in policy. See section on sensitivity runs.

DONE

Specific Comment P.18, L21 ff:

As mentioned, I don't believe in constantly repeating things. Scientific papers are meant to be concise.

We have already put a cautioning remark on the most prominent DICe problems in the introduction, and expanded the section in the discussion on how these problems may affect our results, and repeated that CDR and adaptation are not included (even though tradeoff between SRM and adaptation and CDR would be important to study in folow-up research).

We also want to do an additional sensitivity study on abatement costs (See answer to comment p17, l1), to get a better idea of how large the influence of this effect on the policy. DONE

Specific Comment P.19, L5-7

Concerning what is / is not included in damage function, see numerous previous comments.

Added "...uncertainties, especially concerning efficiency and damages of SRM and *the extent by which SRM can* mitigate damage inflicted by global warming" DONE

Specific Comment P.20, L.30 ff

Interesting remark, although not of practical importance here, because throughout all simulations, no situation occurs in which the planet is too cool. As a side remark, adding CFCs or HFCs would not be exactly reverse SRM, because for example the effect on precipitation would be different.

Technical comments

- P1L1: we keep in spite of, to stress that (unlike abatement or CDR) SRM has impact even though greenhouse gas concentration remains high.
- P1L8: no "can" found in this line. changed "cannot replace but only complement" to *"can not* replace but only complement" to elucidate the structure of the sentence.
- P1L14: I see your point, but the reference was more to the geoengineering as such, not to the history of the discussion of geoengineering.
- P1L20: the connection with volcanic eruption is made just 1 sentence later, so I'd prefer to not make this sentence overly clumsy.
- P1L21: thanks, corrected.
- P2L4: reformulate for clarification
- P2L23-24: Moreno-Cruz corrected. that: corrected
- P8L2: refers to Heutel's parametrisation for CO2-related damage (not ours). Rephrased.
- P10L18: indeed, SO2 is injected (and leads to sulphate formation). Clarified.

- P12L10: corrected
- P13Fig3: time axis: because we were interested in how tipping continues in the course of time. For the other plots we zoomed in on the first ca 300 years for better readability, because nothing interesting happens in the last 100 years. (will clarify)
  We prefer not having the same y-axis for the mentioned graphs because then some graphs become very hard to read, especially SRM plots in simulations with abatement.
  Spelling: thanks, will be corrected. DONE
- P14L8: performance is explained in eq. 11
- P14L9: the simulation goes to year 2400 even though the graphs do not (see remark above). CDR is not modelled, as you know.
- P20L21: this means that for "safety", the actual margin is made wider than the one suggested by the test trajectories, namely by adding 30% to the maximum and subtracting 30% from the minimum.
- P22ff: Stanford: corrected; title case: sorry, what is meant by this?; ncomms=nature communications (journal); Stowe: corrected.

Reply to Reviewer 2

June 6, 2019

First, a more interesting question about SRM is, to me, not the precise level at which we should be using it now but whether we should start using it at all. The current model has no force that would lead a policymaker to delay introducing SRM. I can think of two relevant forces. First, there may be a fixed cost to beginning SRM, whether political, economic, or ecological. Second, the authors assume (I think) that the risk of SRM failure is constant over time. A more realistic model would have a small chance of new research finding a fatal flaw in SRM as long as it is not used and a much larger chance of actual consequences revealing a fatal flaw once it is used. I am suggesting that the probability of failure should be low as long as SRM is not used and then be higher once it is used. A policymaker might then choose to delay beginning SRM until it is really needed, since SRM may not last for long once it is begun. I strongly encourage the authors to explore these (or other) ways of making the paper about when to begin using SRM.

While in the standard scenarios (section 3.2) we indeed assumed constant failure probabilities for simplicity, the failure probability is time dependent in the "realistic storyline" (Section 3.3), although it is still exogenous, i.e. independent of whether SRM is used yet.

Unfortunately, in the dynamic programming procedure, very high additional computational costs are incurred for adding another state variable, for example for tracking the history of whether and when SRM has started. This makes it very cumbersome to include costs depending on how long ago SRM started (e.g. an initial cost to be payed when starting SRM).

As a compromise, we have run a set of simulations with various (high) costs in case of SRM failure, similar to the termination shock damage in section 3.3. The aim is to investigate whether the fear of very large risk associated with SRM failure might lead to delay (of strong decrease) of deployment. SRM is suppressed until the climate tipping threshold of 2K is reached. See new sect. 3.4.

DONE

Second, the interesting aspect of SRM value is, to me, its insurance value. The authors analyze a dynamic programming problem, so they have the machinery to answer that kind of question, but they fail to get there. Instead, they analyze perhaps the least interesting form of "tipping" that they could have. Their tipping point permanently reduces economic output, but the interesting aspect of SRM in a world with tipping points is the potential for SRM to manage a tipping process that is underway. Had the authors chosen to model tipping points in the way that Lemoine and Traeger (2014) did (where a tipping point is a sudden change in a parameter of the physical system, which manifests itself in temperature and economic output only over time and in a fashion that depends on subsequent policy), SRM could play a key role by allowing the policymaker to intervene after triggering a tipping point so as to mitigate the consequences of that tipping point. Alternately, had the authors studied uncertainty about future warming, SRM could have been used to control the consequences of ending up in a high-warming world. Finally, if the model allowed for the more interesting type of tipping point (or for warming uncertainty) along with a reason to delay beginning SRM, then we may see the policymaker delay SRM until a bad state of the world warrants using it. Learning whether/when that plan is optimal would be interesting..

https://are.berkeley.edu/~traeger/pdf/Lemoine%20Traeger_ Watch%20your%20Step_ AcceptedAEJPolicy.pdf

This alternative climate tipping point is a very interesting suggestion, thank you very much.

We have added a simulation based on the Abatement+SRM where we replaced the damage tipping point by a "sudden warming" tipping point. If this tipping point is triggered, an additional positive radiative forcing contribution F_{alb} will be added to F (which can be thought of as an unexpectedly strong albedo feedback).

The additional forcing obeys:

$$F_{alb} = \alpha_{alb} \max(T - T_{alb}, 0) \tag{1}$$

and the tipping probability obeys the same equation as for the damage tipping point, except that $T_{alb} = 1.5K$ is chosen as threshold.

Note that this tipping point is reversible in the sense that F_{alb} can decrease again if T decreases.[1]

The result is, interestingly, that if he may use SRM, the policy maker does not try to avoid this tipping point. Rather, in case the tipping point is crossed, he reacts by increasing SRM afterwards such as to offset the warming induced by this (reversible) tipping point.

The results are described in more detail in the new section 3.4.

For "delaying" SRM, see answer to the previous comment. In the scenario with the albedo tipping, SRM is increased in case of hitting the tipping point, but it is already used before.

DONE

SMALLER COMMENTS

The authors should spend more space clearly laying out the methodological, calibrational, and conceptual contrasts with Heutel et al. They also should elaborate on the differences in results and speculate as to their origin,

Main Methodological differences between our study and Heutel 2018:

- Their optimisation scheme is a 4-day look-ahead scheme, which is not suitable for long-term optimisation.
- They use a different technique to take into account uncertainty of "how harmful unmitigated CO2 is" and how damaging SRM is, namely by assuming the policy maker to be uncertain about climate sensitivity and SRM damage (without learning). In contrast, we use tipping and SRM failure. (Incorporating parameter uncertainty would be very computationally demanding using dynamic programming.)
- Their climate-related damage function is split in a different fashion, ignoring residual climate change (they do include direct effects from CO2, though).
- SRM implementation costs and damages are both implemented in an implausible fashion, namely as being proportional to the *fraction* of CO2-induced radiative forcing removed by SRM. I.e. it does not matter whether the CO2 forcing is strong or weak; the damage induced for compensating X % of this forcing remains the same. In particular, the fact that a high CO2 content requires absurdly high SO2 emission rates (making a full compensation of global warming undesirable) is not included; the maximal damage from SRM is 3% of GDP (full compensation of CO2-induced forcing); we have no such limit.

The effects of the first item onto the results are hard to predict - their optimisation scheme *might* yield unreliable results, but we cannot tell a priori if this will have a strong impact and to which direction.

The second item: Uncertainty in the "harmfulness of CO2" (climate sensitivity in Heutel; tipping in our study) has a larger policy impact in Heutel, at least for the Abatement+SRM-like scenarios in absence of SRM failure, because in our study, Abatement+SRM keeps below the tipping threshold.

The third item would - at least if the SRM-related damage and implementation costs were equal - probably lead to more SRM in Heutel, because SRM always diminishes climate-related damage (namely, the 80% associated with temperature). In our results, even if SRM caused no damage or cost on its own, it would be optimal to compromise between temperature-related and rainfall-related (residual) damage. However, this might be a minor effect.

The last item causes the most obvious differences. In Heutel's case, the higher the CO2 concentrations (and thus the more global warming), the higher the fraction of greenhouse gas forcing that on wants to balance by SRM, as one deletes more global warming damage for the same SRM-induced cost. So Heutel should be more (less) inclined to rely on SRM for high (low) CO2 concentrations, compared to our model.

It seems that in their deterministic results (Heutel et al., 2018; fig. 2), their peak SRM happens to be somewhat similar to ours: In their year 2140, the highest atmospheric CO2 content is about 1800GtC, leading to a forcing of about 6W/m^2, of which they compensate about 50%. In our model, compensating 3W/m^2 of radiative forcing requires 27Mt(S)/yr; similar to our peak abatement of 35Mt(S)/yr (which we reach later than 2160, namely around 2220; see our fig. 2b). However, around 2020, Heutel et al. compensate 10% of a radiative forcing of 1.6W/m^2,

[1] This is why it makes actually more sense to think of this stylised tipping point as related to albedo, rather than methane release from permafrost, as we suggested in the first version of the letter to the reviewer. Released methane would stay in the atmosphere for some time. However, for computational reasons we did not want to introduce another time-dependent variable for the methane stock.

which is equivalent to about 1.5Mt(S)/yr in our model. In our results, the injection rate around 2020 is almost 10W/m^2 (compensating 1.5W/m^2 of radiative forcing). So basically, especially during the first 100 years or so, while CO2 concentration is not yet so high, Heutel et al. use considerably less SRM, because they overestimate its cost (i.e. ignore that for low CO2 concentrations, there is relatively little radiative forcing that needs compensation). This might explain why they get higher temperatures than we (see their fig. 2d and ours).

Although they do not explore it, if Heutel et al. had used some high-emission scenario like SRM-only, they would unrealistically find that they can always eliminate 80% of their climate damage (the temperature contribution) for a max. cost of around 3%GDP (max. SRM damage), which would imply that SRM is a very good emergency technology (in case that for some reason abatement is not working or in case of unexpected CO2 release from permafrost).

We will include an abbreviated version of this comparison (focusing on the fourth methodological difference) into the discussion section of our paper.

DONE

-Technical notes: 1) The authors describe how they mitigate the problem being non-smooth, but it seems far more straightforward and more realistic to simply assume that the chance of tipping is smooth. Assuming no risk of tipping below some temperature is arbitrary.

2) The authors impose an upper bound on injection rates. This is a curious choice. I would prefer the authors to model the source of the constraint. As it is, either the constraint binds or it does not. If it binds, then it is important, the authors should highlight it in their results discussion, and the authors should consider eliminating it. If it does not bind, then it is unimportant and the authors should consider eliminating it (or at worst justify it in terms of numerical convenience but say it is irrelevant in practice)

1) Any choice of ill-constrained parameters is inherently arbitrary. Ours was inspired by the Paris agreement of staying "well below" 2K warming, because additional warming would be "too dangerous". We could of course have picked a different threshold, such as 1.5K or 0K, or a quadratic increase of tipping probability with temperature. Note that although the 2K (or maybe 1.5K) threshold may be hard to justify on physical grounds, it does match the current political approach of trying to avoid crossing a certain temperature threshold.

We have performed a sensitivity run using 1K as threshold in the standard Abatement+SRM scenario. The effects on policy are very small (see section on sensitivity runs).

DONE

2) Yes, indeed, a threshold was needed for numerical reasons. It has no practical consequences except towards the end of the SRM-only run (which is a somewhat unrealistic scenario anyway). We will clarify this in the manuscript.

DONE

Sensitivity checks: I want to see more sensitivity analysis with respect to the fairly arbitrary damage parameters, and especially to the ψS that I'm not sure has been explored. This should be the core of the results. I am far more interested in learning about what we need to believe to get near-term SRM to be high or low than in learning about the spread of future policy.

We already have a sensitivity run with ψ_S doubled; this leads to a slightly faster abatement (6 years) and lower peak SRM (ca 23% reduction), but no qualitative change in policy. We now also included a simulation with ψ_S halved. Again, there in no qualitative change in the policy (SRM increases by 25% and Abatement is slightly delayed).

DONE

-I wasn't happy with the discussion of precipitation damages in 2.1.3. There are plenty of ways precipitation can matter, independently of temperature. Think of crops. One could have just as easily said that many temperature channels are mediated by precipitation. Plus geoengineering changes precipitation in ways that are not merely determined by temperature. For instance, might geoengineering change patterns of rainfall (such as monsoons)? Perhaps these kinds of effects could be captured by ψS, about which very little is said other than that its level is arbitrary.

I do not fully understand this remark. We did assume that precipitation can matter independently of temperature, that's why we split the damage function into a precipitation and a temperature component (which are differently affected by SRM).

It was mentioned at the end of 2.1.1 that global mean precipitation changes serve as proxy for the residual climate change - similar to the way that Nordhaus uses temperature change as an indicator for "climate change", including changes which are not directly caused by temperature (e.g. rainfall changes). Nordhaus needed only one climate indicator, because he could assume that all climate change somehow scales with temperature, while we must differentiate between climate change that can / can not be mitigated by SRM.

An interesting aspect about precipitation change is that SRM and CO2 have opposing effects and can balance each other. Therefore even if SRM caused no damages or costs on its own, it might be beneficial to compromise between reducing warming and precipitation changes. This interplay would be lost if precipitation damages were simply included into ψ_S.

We will add a remark for clarification. DONE

-The objective in (10) must be wrong. I think the policymaker must be maximizing expected welfare, not just welfare. And in light of that comment, the motivation for the final paragraph in 2.2 doesn't make a lot of sense. A risk-averse policymaker (as modeled here) has already chosen policy in light of the range of possible cases. It is not internally consistent to postulate caring about percentiles of the subsequent policy performance because of risk aversion.

On eq. 10: indeed, in the stochastic case one must optimise *expected* welfare. We corrected this in the text above the equation (W defined in eq.10 is supposed to be the welfare of a specific realisation, and the expectation value of W is to be optimised. DONE

Concerning the motivation of the final paragraph of 2.2: I do not fully agree. Even if one chooses expected welfare as objective for the optimisation, it is interesting to at least look at other criteria such as the percentiles used here (for example, a policy maker might still want to know the probability of "something going quite wrong" under a certain policy). In particular for the realistic storyline scenario, in which SRM is only available with certain probability, it is also insightful to consider not only the mean but include more measures (to verify that the increase in expected welfare compared to Abatement-only comes from those simulations where SRM became available).

We will clarify in the text that the additional measures are not used as optimisation objectves but for additional information only. DONE

-In s 3.2, the authors report that abatement decreases after triggering a tipping point. This is purely an artifact of the type of tipping point modeled here. It would probably not arise if abatement had any role in controlling the consequences of a tipping point, as in Lemoine and Traeger 2014.

Indeed, with the albedo tipping point (see major comment 2), abatement goes up, not down, after hitting the tipping point. We will point this out, also in the context of the new albedo tipping point. DONE

-Why is the scc unaffected by the possibility of tipping in the abatement+SRM world?

There might be a small effect which however is so small that it vanished when rounding to whole dollars. The reason why this effect is small is that tipping is quite unlikely in this scenario, especially at the early (less discounted) time steps, because unless SRM fails, the temperature is kept below the tipping threshold.

-It seems to me that the final sentence on page 16 would be stronger with a comparison between maximized welfare in the "realistic" world and welfare in the same world if the policymaker used the policy from the abatement-only world. How much could today's policymaker gain by anticipating the future possibility of SRM?

That very last sentence on p16 was meant not so much to stress the potential gain, but to warn against slackening abatement while SRM is uncertain. We will stress your point in earlier in the paragraph and reformulate the last sentence to make this more clear. In particular, we will clarify that for the "realistic" scenario, there is a welfare gain by almost 200% in those cases where SRM becomes available (compared to the "abatement-only" case). DONE

-The discounting result in 3.4 was one of the more interesting results of the paper: a higher discount rate favors SRM because it causes damages, may fail, and doesn't curb future CO2. I would suggest highlighting it more and perhaps doing more with it.

We will highlight the result by mentioning it in the conclusions (to further stress that abatement is indispensable, especially if one "cares much about the future", while SRM is more a short-term measure). DONE

List of substantial changes

June 6, 2019

New simulations

- Added two additional scenarios on SRM as insurance (see new section 3.4, also P10L1-9, and)
- Added sensitivity studies: faster decline of abatement cost; reduced damage from SRM; lower tipping threshold. See current section 3.5, particularly table 4.

Major textual issues (clarifications, corections, etc):

- P2L13: added comparison SRM cost - estimate for abatement cost
- P2L29ff: added explanation of major shortcomings of DICE model
- P3L11-12: clarified codes on which we built
- P3L18: corrected error (missing exponent γ_{SO2}) in eq.1 (not pointed out by reviewer)
- P3L27: added troposphreic ozone as important non-CO2 greenhouse gas
- P4: Added some parameters to the table, line 20-23 and 25-27
- P5L19-23: clarified that limit on SRM is due to numerical constraints but of little importance in nearly all simulations
- P6L22ff: better explained precipitation response
- P7L5-7: added clarification about splitting precip. response into temperature-driven and fast response
- P7L20-24: added equation on abatement cost in order to provide context for the new sensitivity run with faster decrease of costs.
- P7L29-31: clarified why we assumed SO2 and not H2S to be used for SRM
- P8L6-11: Improved explanation concerning splitting the damage function
- P9L21-23: Justfied choice of 2K as tipping threshold

- P9L26-28: Justified assumption that SRM might be abandoned
- P9L31-32: clarified that econ. damage associated with SRM failure does occur in some of the scenarios
- P10L1ff: explained albedo tipping point (See sect. 3.4)
- P10L14: corrected ambiguity: the quantity to be optimised is the expectation value of the welfare (and welfare is defined in eq. 12)
- P11L4-5: clarified that expectation value of the welfare (and not percentiles considered below) is the quantity to be optimised.
- P11L17-18: menioned that no-policy scenario is also computed (as benchmark)
- P11L21-30: justified delay of SRM availability in Realistic Storyline scenario and added clarifications, in particular on termination shock.
- P13L16-18: pointed out that SRM might serve as transition technology to "shave off" a warming peak temporarily until abatement shows sufficient effect
- P13L26: clarified that abatement is needed to stabilitse temperature in the long run
- P14L7-8: pointed out that reduction in abatement after hitting the tipping point is to some extent caused by our implementation of tipping points.
- P18 last paragraph: clarified that better performance of "realistic Storyline" vs "Abatement only" is due to those ensemble members where SRM is made available. stressed more clearly that abatement should not be strongly reduced at current stage while SRM is still quite uncertain.
- sect.3.4 and fig. 5: new scenarios on insurance behaviour mentioned in beginning of this list.
- p20, last full paragraph: senitivity run with quickly-decreasing abatement costs
- p21, text and table 5: added sensitivity studdies with lower tipping threshold and lower SRM damage (see beginning of this list)
- p22, first paragraph of sect.4: pointed out impact of reduced rate of pure time preference and possible role of SRM as "insurance"
- P22 second last paragraph: added comparison with study by Heutel
- P23 second last paragraph: expanded explanation of how shortcomings of DICE might affect results

For the minor changes, such as typos, small reformulations, added references to equations within table 3, etc, please consult the change track document.

Complementing CO_2 emission reduction by ~~Geoengineering~~ Solar Radiation Management might strongly enhance future welfare

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Abstract. Solar Radiation Management (SRM) has been proposed as a means to reduce global warming in spite of high greenhouse gas concentrations and to lower the chance of warming-induced tipping points. However, SRM may cause economic damages, and its feasibility is still uncertain. To investigate the trade-off between these (economic) gains and damages, we incorporate SRM into a stochastic-dynamic integrated assessment model and perform the first rigorous cost-benefit analysis of sulphate-based SRM under uncertainty, treating warming-induced climate tipping and SRM failure as stochastic elements. We find that SRM has the potential to greatly enhance future welfare and ~~should therefore be~~ merits being taken seriously as a policy option. However, if only SRM and no CO_2 abatement is used, global warming is not stabilised and will exceed 2K. Therefore, even if successful, SRM ~~cannot~~ can not replace but only complement CO_2 abatement. The optimal policy combines CO_2 abatement and modest SRM and succeeds in keeping global warming below 2K.

1 Introduction

Despite the Paris agreement target to keep global mean temperature change "well below 2K" in order to prevent "dangerous climate change" (UNFCCC, 2015), no decisive reduction of CO_2 emissions has yet taken place (Le Quéré et al., 2018). This has sparked renewed interest in the possibility of cooling the climate system by geoengineering (Crutzen, 2006). Among several suggested approaches, only Solar Radiation Management (SRM), i.e. reflecting part of the incoming solar radiation back into space, has the potential to offset the global mean temperature changes projected by 2100 (Keller et al., 2014).

Of several proposed SRM techniques (Latham et al., 2008; Ahlm et al., 2017; Gabriel et al., 2017; Seneviratne et al., 2018), sulphate aerosol-based SRM is most likely to become feasible in the near future (McClellan et al., 2010; Moriyama et al., 2017). The scheme involves injecting precursor gases such as SO_2 into the stratosphere. This leads to the formation of reflective sulphate aerosols in the lower stratosphere which increase the Earth's albedo and cause surface cooling. Such cooling – of about 0.4K over several years (Stowe et al., 1990; Thompson et al., 2009) – was observed following the Pinatubo eruption (Stowe et al., 1990; Thompson et al., 2009; Stenchikov et al., 1998; Robock, 2000) which injected 8-10 Mt(S) (megatonnes of sulphur), mainly as SO_2, into the stratosphere (Ward, 2009). It is still uncertain whether SRM can completely eliminate future global warming. High aerosol concentrations lead to faster coagulation, which reduces albedo and accelerates deposition (Visioni et al., 2017). One study (Kleinschmitt et al., 2018) suggests that the achievable forcing is limited to SRM cannot provide a stronger negative radiative forcing than $-2W/m^2$, while others find that sufficiently strong forcing can be achieved, albeit at very high injection rates (Niemeyer and Timmreck, 2015; Niemeyer and Schmidt, 2017).

The potential benefits of SRM are obvious: a reduction of global warming and associated warming-induced damages, and a reduced transition likelihood of temperature-related climate tipping points (Cai et al., 2016). However, SRM cannot avert all climate change (Kravitz et al., 2013). In particular, global mean precipitation is expected to decrease (Andrews et al., 2010; MacMartin and Kravitz, 2016), and the spatial precipitation patterns may change. Ocean acidification will continue unless atmospheric CO_2 concentrations are reduced (Tjiputra et al., 2015).

The implementation costs of sulphate SRM are estimated to be $2-10\times10^9\$/Mt$ of injected gas (McClellan et al., 2010; Moriyama et al., 2017), which is modest compared to the world GDP of $80\times10^{12}\$$ (data for 2017, World Bank (2017)). For comparison, building and installing enough solar cells to meet global energy demand would, at current prices, cost about $2.5\times10^{14}\$$, although prices are decreasing rapidly (Cassedy and Grossman , 2017). However, apart from moral issues (Robock et al., 2009), sulphate SRM may have damaging effects on human health (Effiong and Neitzel, 2016) and the environment (Pitari et al., 2014; Ward, 2009) that are still poorly understood (Irvine et al., 2017). A sudden discontinuation of SRM will cause rapid warming ("termination shock") to levels dictated by greenhouse gas concentrations (Brovkin et al., 2009; Matthews and Caldeira, 2007), which could put more stress on ecosystems and societies than a gradual warming (Trisos et al., 2018).

A cost-benefit analysis of SRM should take into account at At least two major uncertainties are of great importance for cost-benefit analysis of SRM: the possibility of warming-induced tipping behaviour (whose likelihood is reduced by SRM) and the possibility of SRM failure, either by inefficiency or because (Kleinschmitt et al., 2018) or because (unforseen) damaging side-effects force one to abandon it (Robock et al., 2009). In this study we use a stochastic version of the integrated assessment model DICE (Nordhaus, 1992) to compute the (economically) optimal policy including CO_2 abatement and SRM. We hereby expand

Here we build on earlier studies, which often included uncertainty only through parameter sensitivity analysis (Goes et al., 2011; Bahn et al., 2015) or as a simplified two-step decision problem (Moreno-Cruz and Keith, 2013). Two recent studies (Heutel et al., 2016, 2018) include climate tipping behaviour and parameter uncertainty but employ a simple 4-step look-ahead scheme which that is unsuitable for long-term optimisation. We employ dynamic programming (Bellman, 1957) to perform the first rigorous cost-benefit analysis of SRM under uncertainty.

The DICE model has been criticised for being overly simple (Pindyck, 2017). In particular, it employs a very aggregated damage function for assessing the material and immaterial cost of climate change (see Nordhaus and Boyer (2000) for the calibration), which ignores irreversibility of damages and delayed damage (e.g. slow melt of ice caps) and which in later model versions (Nordhaus, 2018) has only received minor updates (Auffhammer, 2018), despite new studies on the subject (IPCC WG2 , 2014). Neither does it include climate adaptation. In addition, DICE has an overly simplified energy sector with exogenous costs for CO2 reduction and does not include negative emission techniques. Finally, assuming only one global "social planner", it disregards the possibility of conflict or imperfect collaboration. Despite these shortcomings, we believe DICE to be a useful testbed for exploratory studies, which should serve as a first orientation and be expanded using more detailed models.

The paper is organised as follows: In Sect. 2.1 we present our model GeoDICE, a stochastic DICE model including Geoengineering, and in Sect. 2.3, we describe the scenarios employed. The results are presented in Sect. 3.1 (deterministic cases) and Sect. 3.2 - 3.3 (stochastic cases), with a sensitivity analysis in Sect. 3.5. A summary and discussion is presented in Sect. 4.

2 Methods

2.1 GeoDICE: a stochastic DICE model including Geoengineering

~~We modified DSICE (Cai et al., 2012), a stochastic version of the DICE model (Nordhaus, 1992), to~~ Our code is based on Cai et al. (2016), which in turn combines the 2013 version of DICE (Nordhaus, 1992, 2018) and the DSICE framework (Cai et al., 2012) for stochastic treatment of DICE. Here, we include SRM as an additional policy option (together with CO_2 abatement). To this end, we incorporate the cooling effect, implementation costs, and environmental damages of SRM into DSICE. A summary of the model parameters and their standard values is given in Table 1.

2.1.1 SRM and Radiative Forcing

To the radiative forcing equation, we add a contribution that depends sublinearly on the sulphur injection rate (Niemeyer and Timmreck, 2015). The total radiative forcing F takes the form

$$F = \alpha_{CO2} \ln((C_{PI} + C)/C_{PI}) + F_{other} - \eta\, \alpha_{SO2} \times \exp[(-\beta_{SO2}/I_S)] \exp[-(\beta_{SO2}/I_S)^{\gamma_{SO2}}] \equiv F_C + F_{other} + F_S. \quad (1)$$

The first term F_C describes the contribution of the increase C in atmospheric CO_2 concentration above the preindustrial value C_{PI} and is the same as in DICE. The second term F_{other} represents the effects of other greenhouse gases (eg. CH_4, N_2O, halogen compounds) and industrial aerosol. In DICE, this term is prescribed. However, it seems unlikely that a society that makes great efforts towards abating CO_2 emissions does nothing towards combatting other pollutants. Based on data from Ciais et al. (2013) we assume that roughly 30% of the current CH_4 emissions (contributions related to fossil fuel production, e.g. leakage, and biomass burning), 10% of the N_2O emissions (likewise from industry and fossil fuel production) and 100% of the emission of halogen compounds could be abated, whereas 70% of the CH_4 emissions (natural sources and agriculture) and 90% of N_2O emissions (agriculture) cannot be abated. Tropospheric ozone, another important greenhouse gas, is formed in chemical reactions with pollutants which likewise can be partially abated. As a rough estimate, about 50% of the radiative forcing stemming from non-CO_2 greenhouse gasses could be abated. For simplicity, we assume that this also holds for (mainly

Symbol	Meaning	Value
α_{CO2}	Effect CO_2 on radiative forcing; see eq. 1	$5.35 W/m^2$
α_{SO2}	scales sulphate radiative forcing; see eq. 1	$65 W/m^2$
β_{SO2}	scales sulphate radiative forcing; see eq. 1	$2246 Mt(S)/yr$
γ_{SO2}	scales sulphate radiative forcing; see eq. 1	0.23
η	sulphate rad. forcing correction; see eq. 1	0.742
b_1	strength temperature response; see eq. 4	$0.126 \frac{K}{W/m^2}$
b_2	strength temperature response; see eq. 4	$0.0254 \frac{K}{W/m^2}$
τ_{T1}	time scale temperature response; see eq. 4	$1.89 yr$
τ_{T2}	time scale temperature response; see eq. 4	$13.6 yr$
p_T	precipitation dependence on temp.; see eq. 6	$0.0806 (mm/day)/K$
p_C	precipitation dependence on CO_2; see eq. 6	$-0.0229 (mm/day)/(W/m^2)$
p_S	precipitation dependence on SRM; see eq. 6	$-0.0077 (mm/day)/(W/m^2)$
ψ_C	econ. damage from CO_2 conc. ; see eq. 9	$1.703 \times 10^{-3} K^{-2}$
ψ_T	econ. damage from warming; see eq. 9	$0.4 (mm/day)^{-2}$
ψ_P	econ. damage from precip. change; see eq. 9	$3.31 \times 10^{-8} (ppmv)^{-2}$
ψ_S	econ. damage from SRM; see eq. 9	$9.27 \times 10^{-5} (Mt(S))^{-2}$
ψ_{fail}	econ. damage from SRM failure; see sect. 3.3	$0.01/Mt(S)$
Ω	remaining fraction econ. output after tipping; see eq. 7	0.9
λ_S	implementation cost SRM; see eq. 7	$14 \times 10^9 \$/Mt(S)$
λ_0	cost of abatement; see eq. 8	2.15
λ_1	cost of abatement; see eq. 8	$0.418 \$/kg(C)$
λ_2	cost of abatement; see eq. 8	2.0
λ_3	cost of abatement; see eq. 8	$0.005 yr^{-1}$
κ_{tipp}	tipping probability per year and K warming; see eq. 10	$0.00255/yr/K$
T_{tipp}	temperature threshold for (damage) tipping; see eq. 10	$2K$
T_{alb}	temperature threshold for albedo tipping; see eq. 11	$1.5K$
α_{alb}	radiative forcing strength for albedo tipping; see eq. 11	$1.07 W/m^2/K$
κ_{fail}	probability of SRM failure per year; see sect. 2.1.4	$0.00056/yr$
ρ	pure rate of time preference (constant in time); see eq. 12	$0.015/yr$
δ_K	rate of capital depreciation; see Nordhaus (1992)	$0.065/yr$

Table 1. Model parameters of the GeoDICE model related to the representation of SRM. The carbon model parameters can be found in Table 5 of Joos et al. (2013), and others in DICE/DSICE (Cai et al., 2012).

cooling) industrial aerosol. Thus we put

$$F_{other} = F_{other,DICE} \times (1 - \kappa\mu),$$

where $\kappa = 0.5$, μ is the abatement of CO_2, i.e. the fraction of CO_2 emissions avoided, and $F_{other,DICE}$ is the prescribed contribution used in DICE.

The third term F_S describes the influence of sulphate SRM. The sulphate injection leads to a (negative) radiative forcing at the top of the atmosphere which is given by $\alpha_{SO2} \times \exp[(-\beta_{SO2}/I_S)^{\gamma_S}]$ $\alpha_{SO2} \times \exp[(-\beta_{SO2}/I_S)^{\gamma_{SO2}}]$, as found in an atmospheric chemistry modelling study (Niemeyer and Timmreck, 2015), where I_S is the annual injection rate of sulphur into the stratosphere (measured in Mt(S)/year).To achieve a modest radiative forcing of $-2W/m^2$ at the Top Of the Atmosphere (TOA), an annual injection of 10 Megatonnes of sulphur (Mt(S)), equivalent to one Pinatubo eruption, is required, whereas to achieve a forcing of $-8.5W/m^2$ (offsetting the greenhouse gas forcing projected for 2100 under the RCP8.5 scenario), 100Mt(S)/year is needed. However, due to fast adjustment processes, the TOA radiative forcing is not sufficient to predict the impact on global mean surface temperature (Kravitz et al., 2015). For example, it is found (MacMartin and Kravitz, 2016) that to compensate $7.42W/m^2$ forcing from quadrupling CO_2, the solar constant would have to be reduced by $(4.2 \pm 0.6)\%$, which amounts to $10.1W/m^2$ TOA (taking into account the Earth's albedo). In other words, the top of atmosphere radiative forcing arising from changes in the solar constant is less efficient than forcing caused by CO_2 by a factor of $\eta = 0.742$. We assume here that sulphate SRM has the same efficiency factor η as solar dimming, since both processes take place above the troposphere, and multiply the sulphate SRM contribution to F by this factor in eq. (1). Note that there is still considerable uncertainty about the forcing efficiency of SRM. For example, Tilmes et al. (2018) find higher efficiencies and an almost linear relationship for injection rates up to $25Mt(S)/yr$, while Kleinschmitt et al. (2018) suggests that the maximal radiative forcing achievable with sulphate SRM might be limited to $2W/m^2$. This possibility that SRM is much less efficient is qualitatively included in the Realistic Storyline scenario described below, which captures that SRM may never work at all. We For numerical reasons, we impose an upper bound of $I_S \leq 100Mt(S)/yr$ on the injection rates, i.e. we do not allow them to exceed ≈ 10 Pinatubo eruptions per year. This upper limit is a much higher injection rate than considered in most detailed studies of the environmental and climate effects of SRM. The limit is never reached except in the somewhat extreme SRM-only scenario (see sect. 2.3).

2.1.2 Carbon cycle and Climate response

We replace the carbon-climate part of DSICE by an emulator of full-fledged climate model simulations (Aengenheyster et al., 2018; MacMartin and Kravitz, 2016). We also include global mean precipitation as a proxy for the residual climate change (changes remaining if SRM is employed to keep global mean temperature constant).

As in DICE, CO_2 can be emitted by industrial processes fossil fuel combustion and landuse change. The former contribution is calculated within our model, the latter is prescribed externally, using the same values as DICE. We model carbon concentrations based on the Green's function found by Joos et al. (2013).

Current CO_2 concentrations $C(t)$ (above pre-industrial) can be computed from emissions E at all previous times $t' < t$:

$$C(t) = \int\limits_{t'<t} G_C(t-t')E(t')dt', \tag{2}$$

where $G(t-t')$ is the Green's function determining how a unit emission pulse contributes to the concentrations $t-t'$ years later, and $E(t')$ an emission pulse at time t'. Following Joos et al. (2013), $G_C(s)$ can be represented as a sum of exponentials, $G_C(s) = a_0 + \sum_{n=1}^{N} a_s e^{-s/\tau_n}$, with $n = 3$, and the temporal evolution of C can be rewritten as

$$C(t) = C_0(t) + \sum_{n=1}^{N} C_n(t), \tag{3a}$$

$$dC_0/dt = a_0 E, \tag{3b}$$

$$dC_n/dt = a_n E - \frac{1}{\tau_n} C_n. \tag{3c}$$

Here a_0 represents the fraction of carbon emissions staying permanently in the atmosphere. The model parameters a_n, τ_n were obtained from a multi-model study (Joos et al. (2013), see their Table 5) and thus represent a best estimate for the behaviour of the carbon cycle, provided that nonlinear effects (e.g. saturation of carbon sinks with increasing CO_2 concentrations) are small. The initial values are $C_0 = 39.01ppmv$, $C_1 = 35.84ppmv$, $C_2 = 21.74ppmv$, $C_3 = 4.14ppmv$, since our model does not start at pre-industrial times (1765) but in 2005.

For the global mean temperature change (relative to pre-industrial), we follow the same approach, fitting the temperature response to a 1-year pulse of radiative forcing obtained by a multi-model study (MacMartin and Kravitz, 2016) onto a sum of exponentials, obtaining

$$T = T_1 + T_2 \tag{4a}$$

$$dT_n(t)/dt = b_n F - \frac{1}{\tau_{Tn}} T_n \tag{4b}$$

where F is the radiative forcing from eq. (1) and other parameters are in Table 1. For the temperature response to a radiative forcing pulse, there is no permanent response T_0. The initial values (year 2005) are $T_1 = 0.466K$ and $T_2 = 0.436K$.

The response of global mean precipitation P to CO_2-induced or SRM-induced radiative forcing is based on MacMartin and Kravitz (2016) and can be split into a slower temperature-driven increase of $2.5\%/K$ and an instantaneous contribution due to CO_2 and SRM (Andrews et al., 2010). In particular, increased CO_2 concentrations cause additional absorption of longwave radiation, warming the atmosphere and causing a more stable stratification, which suppresses precipitation, while surface warming enhances precipitation. For a gradual increase in CO_2 and zero SRM, the temperature-driven effect dominates over the instantaneous contribution, leading to a net moistening. For SRM, the instantaneous contribution is much weaker than for CO_2. More specifically, the response G_P^f of the global mean precipitation P to a one-year-long $1W/m^2$ pulse of radiative forcing from agent f (f stands for CO_2 or a change in the solar constant) in year 0, obtained by MacMartin and Kravitz (2016), can be expressed as

$$G_P^f(t) = b_f \delta_{t,0} + a G_T(t), \tag{5}$$

where G_T is the temperature response to a $1W/m^2$ forcing and $\delta_{t,0} = 1$ if $t = 0$ and 0 else. This means that in the year of the forcing pulse, the fast response b_f plays a role, whereas in later years, the precipitation response is determined by the temperature response. As before, we use the result for reduction in the solar constant as a proxy for sulphate SRM. By lack of data, the fast response to other forcing agents constituting F_{other} is ignored. With these results, the change in global mean precipitation w.r.t pre-industrial can be written as

$$P(t) = p_T T(t) + p_C F_C(t) + p_S F_S(t). \tag{6}$$

Here, where $p_T T$ is the 'slow' precipitation change mediated by warming, whereas $p_C F_C$ and $p_S F_S$ are the instantaneous responses, expressed in terms of the radiative forcings F. Throughout our study, $F_C > 0$ (CO_2 warms the globe) , leads to a positive radiative forcing) and $F_S < 0$ (SRM cools)is used to lower the radiative forcing). As explained above, $p_T > 0$ and $p_C < p_S < 0$. The reason for the last relation is that increased CO_2 concentrations warm the atmosphere more quickly than the sea surface, which temporarily leads to a more stable stratification, suppressing convective rainfall. For SRM, the instantaneous response is weaker. Therefore, if SRM were employed such as to cancel the global mean temperature change ($F_S = -F_C - F_{other}$, hence $T = 0$), the slow responses stemming from temperature change would cancel and the fast response to CO_2 would dominate, reducing P.

We use P as a proxy for residual climate change, i.e. for all effects which remain even if global mean temperature changes are cancelled by SRM.

2.1.3 The Damage function and SRM costs

As in DICE (Nordhaus, 1992), the gross domestic product (GDP) $\bar{Y}$ is diminished by climate-related damage and by expenditures for climate policy (CO_2 abatement and SRM implementation). Including these losses, we retain for the net output:

$$Y = \Omega \frac{1}{1+D} \Lambda \bar{Y} - \lambda_S I_S. \tag{7}$$

Here, Ω describes damage due to tipping points (see sect. 2.1.4). If tipping has occurred, then $\Omega = 0.9$ (reducing the economic output), else $\Omega = 1$ (output not reduced). $D \geq 0$ describes non-tipping damage (discussed below). Λ is a factor describing the abatement costs ($\Lambda < 1$ in case of abatement, and $\Lambda = 1$ in case of no abatement) taken over from DICEDICE-2013 (Nordhaus and Boyer, 2000; Nordhaus, 2018):

$$\Lambda(\mu) = 1 - \Lambda_0(t)\mu^{\lambda_0} \tag{8a}$$

$$\Lambda_0(t) = \frac{\lambda_1 \sigma(t)}{\lambda_2}[\lambda_2 - 1 + \exp(-\lambda_3 t)] \tag{8b}$$

where $\sigma(t)$ is the carbon intensity (amount of carbon released per dollar production, in absence of abatement), and λ_i are constants. Since CO_2 emission is proportional to $\bar{Y}$, so are abatement costs (the more economic output, the more CO_2 emissions and hence the higher the costs of eliminating a fraction μ of these emissions). $\lambda_S I_S$ is the implementation cost of SRM, which

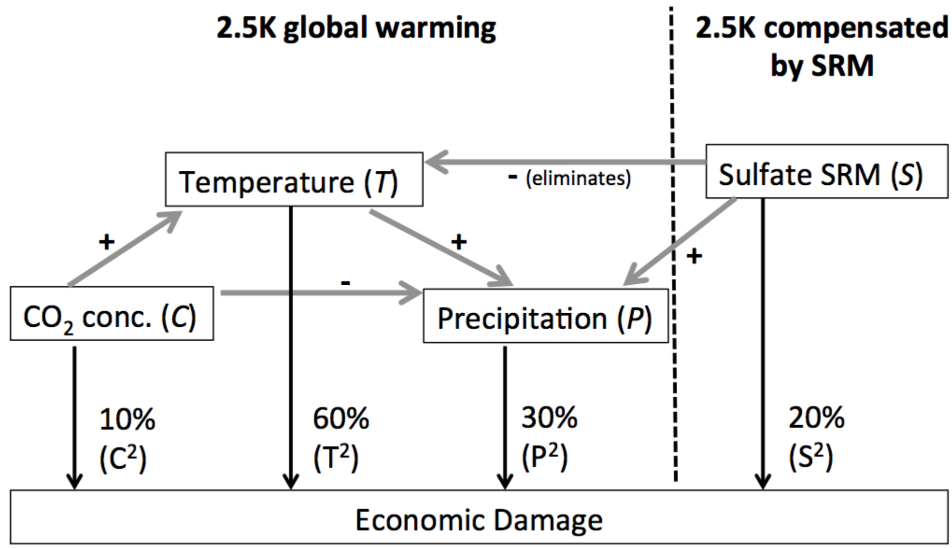

Figure 1. Graphical representation of the damage function. The black thin arrows represent contributions to the damage function, while grey arrows depict how the climate variables influence each other (+ and - stand for increasing and decreasing effects, respectively; see eq. (4) and (6)). The percentages for C, T, and P are based on the contributions of these variables for the standard case of 2.5K warming in equilibrium and in absence of SRM. In this standard case, our damage equals that of the DSICE model (Cai et al., 2012). The sulphur injections that would be needed to offset 2.5K warming cause a direct damage of 20% of the standard damage function.

we assume to be linear in the injection rate I_S and independent of $\bar{Y}$. Two studies (McClellan et al., 2010; Moriyama et al., 2017) suggest that the costs for lifting gasses to 20km height are of the order of $2-10\times10^9\$/Mt$ of injected gas. Taking an intermediate value of $7\times10^9\$/Mt$, and assuming that the gas used is SO_2 (which has twice the molecular weight of elementary S), this amounts to $14\times10^9\$/Mt(S)$. Note that H_2S would have a lower weight per mole of S, which might reduce transportation cost. However, H_2S is also more poisonous and thus potentially harder to handle. To be conservative, we assumed the costlier solution.

While the original DICE model assumes that climate-induced damage D scales with the square of temperature change T ($D(T)=\psi_0 T^2$ with constant ψ_0), we keep the quadratic structure but split the damage function into three climate-related contributions and one contribution representing the damage inflicted by sulphate SRM (see fig. 1):

$$D(T,P,C,I_S) = \psi_T T^2 + \psi_P P^2 + \psi_C C^2 + \psi_S I_S^2 \quad (9)$$

where T, P, C are the changes (w.r.t. pre-industrial) of global mean temperature, global mean precipitation and atmospheric CO_2 concentration, respectively, and I_S the sulphur injection rate in $Mt(S)/yr$. Note that both while SRM counteracts the effect of CO_2 on both temperature and precipitation, the relative influence of the forcing agents on both variables differs, so that it is not possible to compensate the warming and precipitation change at the same time. Both positive and negative precipitation changes P are considered damaging, because both require ecosystems and humanity to adapt. An increase in atmospheric CO_2

may not be damaging in itself, or even benefit plant growth (Ciais et al., 2013); but we consider C as a (rough) proxy for ocean acidification, which we do not model explicitly. The coefficients ψ (values: see Table 1) are chosen such that for the standard case of 2.5K warming in equilibrium without SRM, our total damage equals that of the original DICE model, and the contributions by T, P, and C are 60%, 30%, and 10%, respectively. The standard case was determined by running the climate module of GeoDICE to equilibrium with constant greenhouse gas concentrations, such as to obtain $T = 2.5K$. Following Aengenheyster et al. (2018), and approximately in agreement with RCP scenarios, it was hereby assumed that other forcing agents (other greenhouse gases and aerosols constituting F_{other}) contribute 14% of the total radiative forcing. These other forcing agents are not assumed to cause direct damage. The damages associated with the annual sulphur injections needed to offset a warming of 2.5K are assumed to equal 20% of the standard case damage.

Previous studies (Heutel et al., 2016, 2018) likewise split the damage function, but without including residual climate change (P). ~~They assumed increasing CO_2 concentrations to cause 20~~Heutel et al. (2018) oceanic and atmospheric CO_2 to cause 10% of the ~~damage, evenly split over oceanic and~~ the total damage each (20% in total). However, atmospheric CO_2 ~~. We reduced this to 10% because atmospheric CO_2~~ is not known to cause substantial direct damage and may even be beneficial to plant growth (Ciais et al., 2013)~~.~~, while oceanic CO_2 leads to ocean acidification. As mentioned, we do not explicitly compute oceanic CO_2, but reduce total CO_2-related damage to 10% because half of the total damage in Heutel et al. (2018) seems in fact small. The splitting between T and P is somewhat arbitrary, but is based on the rough assumption that, although precipitation changes can have substantial impact, much of the damage is either determined by temperature (especially sea level rise, a major contributor) or at least strongly influenced by it (e.g. hurricanes), hence $\psi_T > \psi_P$. The damage related to SRM depends on the injection rate, not on the percentage of compensated greenhouse gas forcing as was (somewhat unrealistically) assumed in earlier studies (Heutel et al., 2016, 2018). The choice of ψ_S is again somewhat arbitrary, as virtually no data on the economic damage of SRM is available. However, our main conclusions are unaffected by the exact choice of the parameters ψ (see Sect. 3.5).

2.1.4 Tipping points and SRM failure

Climate change may not only lead to smooth and predictable damages, but also induce low-probability, high-impact, irreversible events such as a collapse of ice sheets (Cai et al., 2015, 2016). The chance of such tipping behaviour is thought to increase with temperature. We take tipping into account in a stylised way, assuming that there is one tipping event that, once activated, reduces GDP by 10% for all subsequent time steps (i.e. $\Omega = 0.9$ in eq. (7)). The likelihood of tipping obeys

$$L_{tipp} = \begin{cases} 0 & T < T_{tipp} \\ (T - T_{tipp}) \times \kappa_{tipp} & T > T_{tipp} \end{cases}, \tag{10}$$

i.e., it is zero if the global mean temperature change ~~$T < 2K$~~$T < T_{tipp} = 2K$, but increases linearly with warming above 2K. While in the real climate system a sharp threshold might not exist, this choice reflects ‘political reality’, in which policy makers set thresholds for ‘dangerous’ climate change to be avoided. The constant κ_{tipp} is chosen such that in a scenario where the policy maker uses only abatement and remains unaware of possible tipping behaviour, the probability of tipping within 400 years is 50%. This order of magnitude of the likelihood and damage of tipping is consistent with earlier studies (Cai et al., 2016).

We also take into account the possibility that SRM has to be abolished(e. g. due to new scientific evidence about unforeseen dangers) . While possible reasons remain speculative at this point, it is not inconceivable that SRM has an unexpected destructive side effect, such as a massive deterioration of the ozone layer. We model this by assuming that each year, there is a probability κ_{fail} that SRM may not be applied anymore in the future. The cumulative probability of SRM failure over 400 years is 20%. Unless stated otherwise, Failure is assumed irrevocable; once failed, SRM remains unavailable forever. In the basic scenarios (see sect. 2.3), we include no economic damage related to SRM failure, because humanity is optimistically assumed to realise such dangers and abandon SRM in time . (see however the Realistic Storyline scenario in sect. 3.3 and the high SRM failure damage scenario in sect. 3.4).

Finally, in the Albedo Tipping Scenario (see sect. 3.4), we replace the damage tipping point described above by a tipping point which causes an additional radiative forcing (thought of as being due to temperature-driven albedo changes), loosely following Lemoine and Traeger (2014). The forcing obeys

$$F_{alb} = \alpha_{alb} \max(T - T_{alb}, 0) \tag{11}$$

i.e., a positive, temperature-dependent forcing occurs if the tipping point is activated and if T exceeds the threshold $T_{alb} = 1.5K$. The tipping probability obeys eq. (10) except that the threshold T_{tipp} is replaced by T_{alb}. Note that this tipping point is reversible in the sense that F_{alb} can decrease again if T decreases.

2.2 Optimisation and Performance Measures

As in DICE, we assume that all decisions are made by a single policy maker who aims to optimise the welfare of the (homogeneous) world population. As in DICE, welfare depends entirely on consumption. The economic output is spent on investment $I = rY$ and global consumption $Lc = Y - I$ where r is the saving rate, and L and c are the world population and per capita consumption, respectively. We assume a fixed saving rate of $r = 22\%$. The utility u (which can be thought of as the current "happiness" of the world population) depends on c: $u = L(c^{1-\gamma} - 1)/(1-\gamma)$ with $\gamma = 2$ and the quantity to be maximised is the welfare (expectation value $\mathbb{E}(W)$ of the welfare W (the time-integrated, discounted utility):

$$W = \sum_t u(t) e^{-\rho t} \tag{12}$$

where t is (discrete) time and ρ the rate of pure time preference. The greater ρ, the less does the far future count towards W. The morally correct value of ρ has been fiercely discussed (Stern et al., 2007; Lilley, 2012; Ackerman, 2007). Here, we will not join the ethical debate on the 'correct' value, but use the standard value of 1.5% and perform a sensitivity study with $\rho = 0.5$ (see Sect. 3.5).

The decision variables are the amount of CO_2 abatement μ (the fraction of CO_2 avoided) and the sulphur injection rate I_S. The model is integrated in yearly time steps, but the decision variables μ and I_S are changed only once a decade to save computational effort. The "policy" (sequence of values for μ and I_S) is optimised such as to maximise the expected welfare (expectation value of W) $\mathbb{E}(W)$ over a time horizon till 2400, though the far future is heavily discounted. The optimisation is performed using Dynamic Programming (see appendix). Once an optimal policy is found, it is evaluated by running an ensemble of 5000 members with this policy and Monte-Carlo realisations of the stochastic elements (climate tipping and SRM failure). The best policy is the one yielding the highest expectation value of the welfare W expected welfare $\mathbb{E}(W)$. For easier comparison, we define a performance measure based on the improvement of W under policy π with respect to a no-action policy ($\mu = 0, I_S = 0$):

$$\zeta(\pi) = 100\% \times \frac{W_\pi - W_0}{W_{AD} - W_0} \tag{13}$$

where W_π, W_0, and W_{AD} are the expectation values over the Monte-Carlo ensemble of the welfare associated with policy π, the no-action case, and the optimal policy for the deterministic Abatement-only case (the policy that would be optimal if the decision maker may only use abatement, and no climate tipping occurs), respectively. By construction, the relative performance is 100% for Abatement-only in the deterministic case.

To evaluate the performance of policies, one may not only be interested in the ensemble mean, but also Although the objective for the optimisation is the expectation value of the welfare, it is also interesting to investigate the range of possible values. In particular, a risk-averse policy maker might also be interested in welfare outcomes, especially the worst (or a at least relatively bad) case scenario. Hence we present two additional performance measures, based on the 10th and 90th percentile of the Welfare welfare W_π. Similar to eq. (13) we define $\zeta_X(\pi)$, the X-percentile relative performance of a policy π, as

$$\zeta_X(\pi) = 100\% \times \frac{W_{\pi,X} - W_0}{W_{AD} - W_0} \tag{14}$$

where $W_{\pi,X}$ is the Xth percentile of the welfare (discounted cumulated utility) for policy π. Note that W_{AD} and W_0 are still the mean (i.e. not percentiles) welfare associated with the optimal policy for the deterministic Abatement-only case, and the no action case, respectively.

2.3 Scenarios

In Sect. 3.1 - 3.2 we first consider three stylised policy scenarios. The first is Abatement-only, in which the decision maker is allowed to use CO_2 abatement but no SRM. The second is SRM-only, in which the decision maker uses only SRM, until an SRM failure occurs, after which only abatement may be used. This scenario represents a society which does not reduce CO_2 emissions but relies entirely on SRM (until it fails). The third is Abatement+SRM, wherein the decision maker can use both Abatement and SRM, unless SRM fails, after which only abatement is used. These three A no-policy scenario with neither abatement nor SRM serves as benchmark for performance comparison (see eq. (14)). These three standard scenarios are first discussed in a deterministic setting (Sect. 3.1), i.e. in absence of climate tipping and SRM failure, before addressing them in the full model with uncertainty (Sect. 3.2).

While the previous stylised scenarios serve to isolate specific effects, we also present a more Realistic Storyline (see Sect. 3.3) where which allows for the fact that it may take time to develop SRM technology, generate a legal framework and public support, and evaluate associated risks. Also, all these proceses may fail or the effectiveness of SRM might be found

Policy	ζ	peak SRM	Ab. 50%	Ab.90%	SCC
Abatement-only	100%	/	2114	2212	35
SRM-only	186%	*	/	/	21
Abatement+SRM	238%	35.1	2134	2243	20

* SRM does not peak, but keeps increasing until the upper limit of $100Mt(S)/yr$.

/ = Not applicable

Table 2. Comparison of policies in the deterministic setting (no tipping, no SRM failure). Abatement-only means that no SRM is used, SRM-only means that no abatement is used (unless SRM fails; see text), and in Abatement+SRM both are used. The performance ζ (see eq. (13)) is a measure of the increase in expected cumulated discounted utility w.r.t. the no-action scenario, and is normalised such as to yield 100% for Abatement-only. The column 'peak SRM' contains the highest SRM values (in Mt(S)/yr) over all time steps. 'Ab 50%' and 'Ab 99%' show the year in which the abatement reaches 50% and 99%, respectively. SCC is the social cost of carbon in the first time step (measured in $(2005)/t(C)).

too low. Therefore we assume that SRM will become possible only in 2055, and only at 30% probability. To be precise, at each time step until 2055, there is an equal probability that humanity discovers that SRM is impracticable. In the first decade where SRM is allowed, there is a 20% probability of SRM failure; in the second decade, 10%; in the third decade 5% and after that 1% per decade, i.e. after some decades of testing, failure becomes less likely. In this scenario, we also investigate the effect of a damage in case of SRM failure ('termination shock'): SRM failure is accompanied by a one-time reduction of the GDP by a factor $1 - \psi_{fail} I_S$ where I_S is the injection rate in Mt(S)/yr and ψ_{fail} is given in Table 1.

3 Results

3.1 The deterministic case

As a reference, we first consider the deterministic case, i.e. without SRM failure and tipping points, in the three stylised scenarios (see Fig. 2 and Table 2). Allowing SRM in addition to abatement delays abatement by 2-3 decades, but does not replace it (Fig. 2a). CO_2 concentrations in Abatement+SRM (Fig. 2c) peak slightly later than in Abatement-only and reach higher values (875ppmv instead of 741ppmv). SRM helps to reduce global warming considerably: The global mean temperature change T peaks at 1.6K for Abatement+SRM, but at 3.1K for Abatement-only (Fig. 2d). SRM slightly deceases towards the end of the simulation, when CO_2 concentration also goes down. This illustrates the potential use of SRM as a transition technology, especially under ambitious abatement: SRM can be used for a limited time in modest strength to cut off a warming overshoot.

In SRM-only, CO_2 concentrations reach 2000ppmv in 2260 and continue to increase (Fig. 2c). Note that currently known fossil fuel reserves are insufficient to generate this much carbon, but it is not impossible that fracking and newly discovered coal deposits will lead to sufficient fuel resources (Cassedy and Grossman , 2017). The temperature increase T continues to rise, reaching 5.4K in 2400 (Fig. 2d), although it is lower than in the no-action case (neither SRM nor abatement). Due to the sub-linear increase of the radiative forcing with SRM, very SO_2 high injection rates would be needed to stabilise T with SRM-

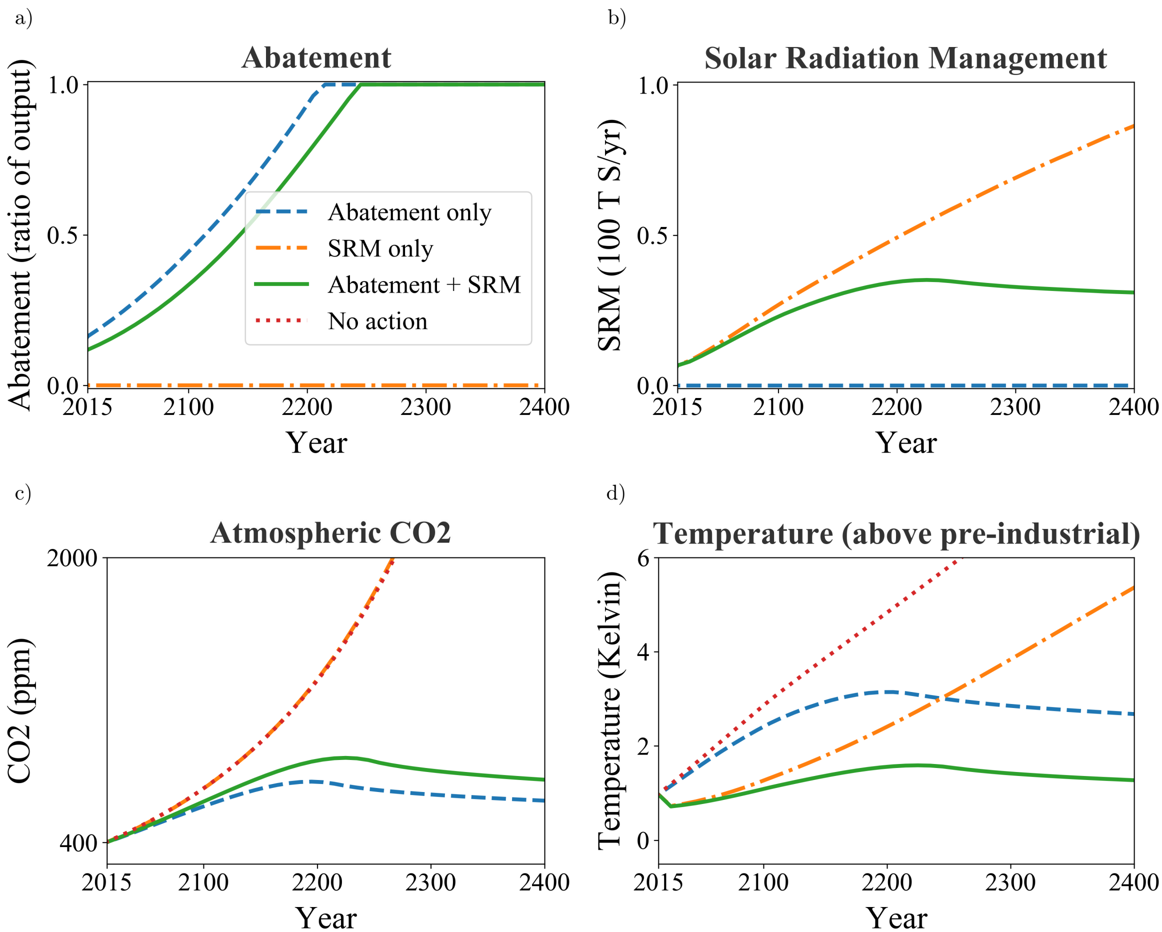

Figure 2. Optimal policy and climate model results for the three stylised scenarios in the deterministic setting. a) Abatement (fraction of CO_2 emissions avoided), b) SRM (Mt(S)/yr), c) atmospheric CO_2 concentration in ppmv, d) global mean temperature above pre-industrial (K). The blue dashed line represents the Abatement-only scenario, yellow dash-dotted: SRM-only, solid green: Abatement + SRM, red dotted (only plot c and d): no climate action (i.e. neither abatement nor SRM).

Policy	ζ	ζ_{10}	ζ_{90}	SRM fail	Tipping	peak SRM	Ab. 50%	Ab.90%	SCC
No action	0%			/	96.2%	/	/	/	45
Abatement-only (det. policy**)	100%			/	49.5%	/	2114	2212	42
Abatement-only	105%	77%	121%	/	37.8%	/	2095	2215	41
SRM-only	181%	179%	185%	19.8%	60.96%	*	/	/	23
Abatement + SRM	219%	220%	223%	20.2%	6.2%	35.0	2139	2242	20
Realistic Storyline	125%	78%	190%	79.9%	30.1%	31.4	2106	2234	37

* SRM does not peak, but keeps increasing until the upper limit of $100Mt(S)/yr$.

** Tipping can occur, but the policy maker ignores this and chooses the policy which would be optimal in the deterministic case.

/ = Not applicable

Table 3. Comparison of policies in the stochastic setting, i.e. including climate tipping and SRM failure. No action means that neither abatement nor SRM are used; other scenarios are explained in Sect. 2.3. The perfomance measures ζ, ζ_{10} and ζ_{90} are given in eq. (13) and eq. (14). The columns 'SRM fail' and 'Tipping' show the probability that SRM failure or climate tipping occurs before 2415. The column 'peak SRM' contains the highest SRM value (in Mt(S)/yr) over all time steps and over all ensemble members. This corresponds to members in which no SRM failure or climate tipping occurred, at least before the time of the SRM peak. 'Ab 50%' and 'Ab 99%' show the year in which the abatement reaches 50% and 99%, respectively. SCC is the social cost of carbon in the first time step (measured in $(2005)/t(C)).

only, so that the damage related to sulphate injection outweighs the climate damages. Compared to SRM-only, considerably less SRM is needed in Abatement+SRM, namely $\approx 35Mt(S)/year$ (Fig. 2b; $3-4$ Pinatubo eruptions per year), yet T remains much lower. This suggests that abatement is required in order to achieve long-term temperature stabilisation.

The relative performance $\zeta(\pi)$ for SRM-only and Abatement+SRM, becomes 186% and 238%, respectively (see Table 2). (By construction, $\zeta = 100\%$ for Abatement-only in the deterministic setting.) The reason for the better performance of SRM-only compared to Abatement-only is that SRM-only yields lower temperatures and a higher utility in the first two centuries, which contribute most to the cumulative utility due to discounting. In addition, postponing damage is beneficial as it allows more time for accumulating capital.

3.2 The effect of uncertainties

Next, we include the stochastic elements, temperature-induced tipping and SRM failure, and determine again the optimal policies for each scenario, prior to evaluating the optimal policy by means of a Monte-Carlo ensemble (see Sect. 2.2). In Fig. 3b - l, we plot the policy (abatement and SRM) carbon concentration and temperature for the three stylised scenarios. The plots depict some sample paths of ~~individuals~~ individual Monte-Carlo runs (thin blue lines), the range of possible outcomes (shading) and the ensemble mean (red line). For comparison, the results from the deterministic case (compare Fig. 2) are also plotted (blue dashed lines).

In the Abatement-only scenario, the danger of tipping initially leads to higher abatement (Fig. 3d) than in the deterministic case, although the temperature is not kept below the $2K$ threshold (see Fig. 3j). If tipping occurs, the abatement decreases

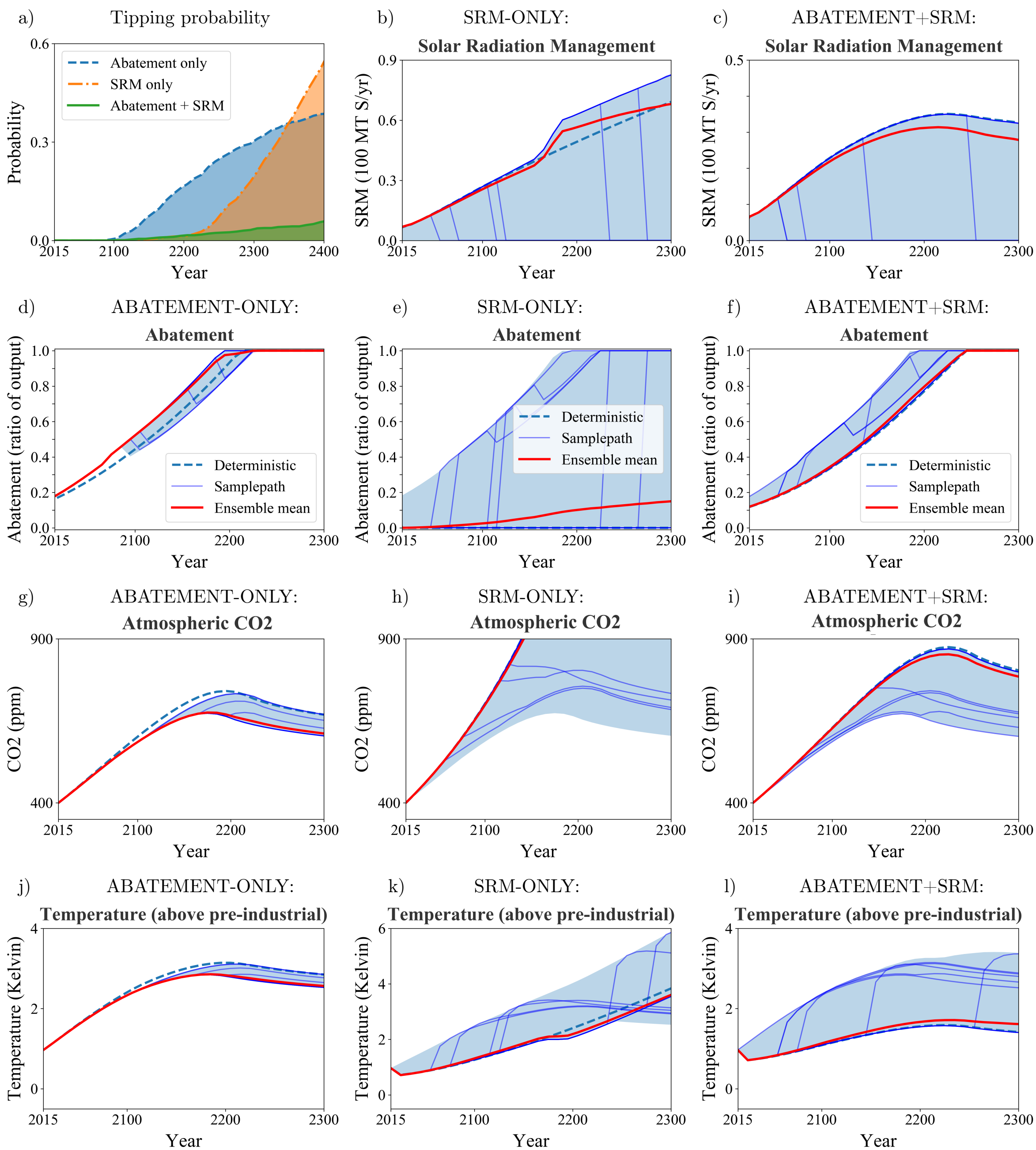

Figure 3. Tipping risk and policy in the stochastic setting (i.e. with tipping point and SRM failure). a) cumulative probability of tipping for Abatement-only (blue dashed line), SRM-only (yellow dash-dotted) and Abatement+SRM (green solid). b)-l): policy and climate response for the same scenarios (zoomed in on years 2015-2300 to enhance readability), namely Abatement-only (left column, plots d),g),j)), SRM-only (middle column, plots b),e),h),k)), and Abatement+SRM (right column, plots c),f),i),l)). Variables shown are: SRM deployed (first row, plots b), c)); note the different y-axis scale), abatement fraction (second row, plots d),e),f)), atmospheric CO2 content in ppmv (third row, plots g),h),i)), and global mean temperature change (last row, plots j),k),l); note the different y-axis scale). ~~In plots b-l) only the first 285 years of the simulation are shown.~~ The thin blue lines represent a sample of individual ensemble members, the thick red line the ensemble mean, and the blue shaded area indicates the range of possible values in the whole ensemble. The dashed blue line depicts the results from the deterministic case (Fig. 2) for reference.

again, as there is no further tipping point to be avoided. (This effect is caused by having a single tipping point which, once activated, does not react to system changes. Compare the Albedo tipping point in sect. 3.4.) The relative performance is 105% (see Table 3, row 3), i.e. it slightly improves when the decision maker takes tipping into account (compare Table 3, row 2). Recall that the reference scenario for W_{AD} uses the policy that would be optimal in absence of tipping, i.e. the policy maker ignores climate tipping.

In the Abatement+SRM case, the optimal policy closely resembles the deterministic one if no SRM failure occurs (Fig. 3c,f). Without SRM failure, T stays below $2K$ (Fig. 3l), and hence no tipping occurs. In case of an SRM failure, the temperature suddenly increases and abatement suddenly increases, as the decision maker now tries to limit the warming (and tipping risk) with only abatement. Note that such a sudden increase in abatement may not be feasible in reality. If climate tipping occurs, abatement is reduced again. Compared to Abatement-only, the abatement is delayed by 3-4 decades.

In the SRM-only scenario, the policy again resembles the deterministic case provided no SRM failure occurs and T is below 2K (Fig. 3b). When $T = 2K$ is reached, SRM increases sharply to reduce the tipping risk. As before, abatement strongly increases after SRM failure, but is reduced slightly if tipping occurs (Fig. 3e). SRM-only has a performance of 181%, much higher than Abatement-only. However, the chance of climate tipping by the year 2415 is considerably higher for SRM-only (61.0% vs 37.8% for Abatement-only, see Table 3). As in the deterministic setting, the reason is that initially SRM can control the global warming more effectively than abatement, while abatement is a long-term measure. Hence damage is postponed to the far future which is heavily discounted. The cumulative probability of tipping is lower for SRM-only than for Abatement-only until 2350, when the situation reverses (Fig. 3a).

Compared to the deterministic cases, including uncertainty slightly reduces the difference in relative performance between Abatement-only and the scenarios using SRM (compare Table 3 vs Table 2). There are two competing effects: The danger of tipping might favour using SRM, which reduces the tipping probability in the near future, while the possibility of SRM failure reduces the performance of SRM-based scenarios.

In Abatement-only, there is a high spread between the relative performance measures ζ, ζ_{10} and ζ_{90}, compared to SRM-only and Abatement+SRM. This is due to the fact that in most ($> 90\%$) of the ensemble members, SRM keeps global warming below 2K at least until ≈ 2200. Hence SRM postpones climate tipping into the far future (except in the few ensemble members with early SRM failure), while for Abatement-only, tipping can occur as early as 2080. Early tipping greatly reduces the performance because it reduces the GDP for a long period of time and because it is less heavily discounted. For Abatement+SRM, only 6.2% (i.e. $< 10\%$) of the ensemble members show climate tipping, but they strongly affect the mean performance. This explains why, for this scenario, $\zeta < \zeta_{10}$.

Although DICE is too limited to give reliable absolute values of the Social Cost of Carbon (SCC) (van den Bergh and Botzen, 2015), comparing scenarios gives qualitative insight into how SRM affects the SCC (Table 2 and Table 3). For Abatement-only, the SCC in 2015 is $35\$/t(C)$ (in 2005\$) in the deterministic case and $41\$/t(C)$ when including tipping points. For Abatement+SRM, the SCC is $20\$/t(C)$ (both deterministic and stochastic): SRM lowers the SCC by partially compensating the damage caused by CO_2 emissions. For SRM-only, the SCC is only slightly higher, namely $21\$/t(C)$ (deterministic) and $23\$/t(C)$ (stochastic), because SRM suppresses most climate damage in the near future, which is discounted least.

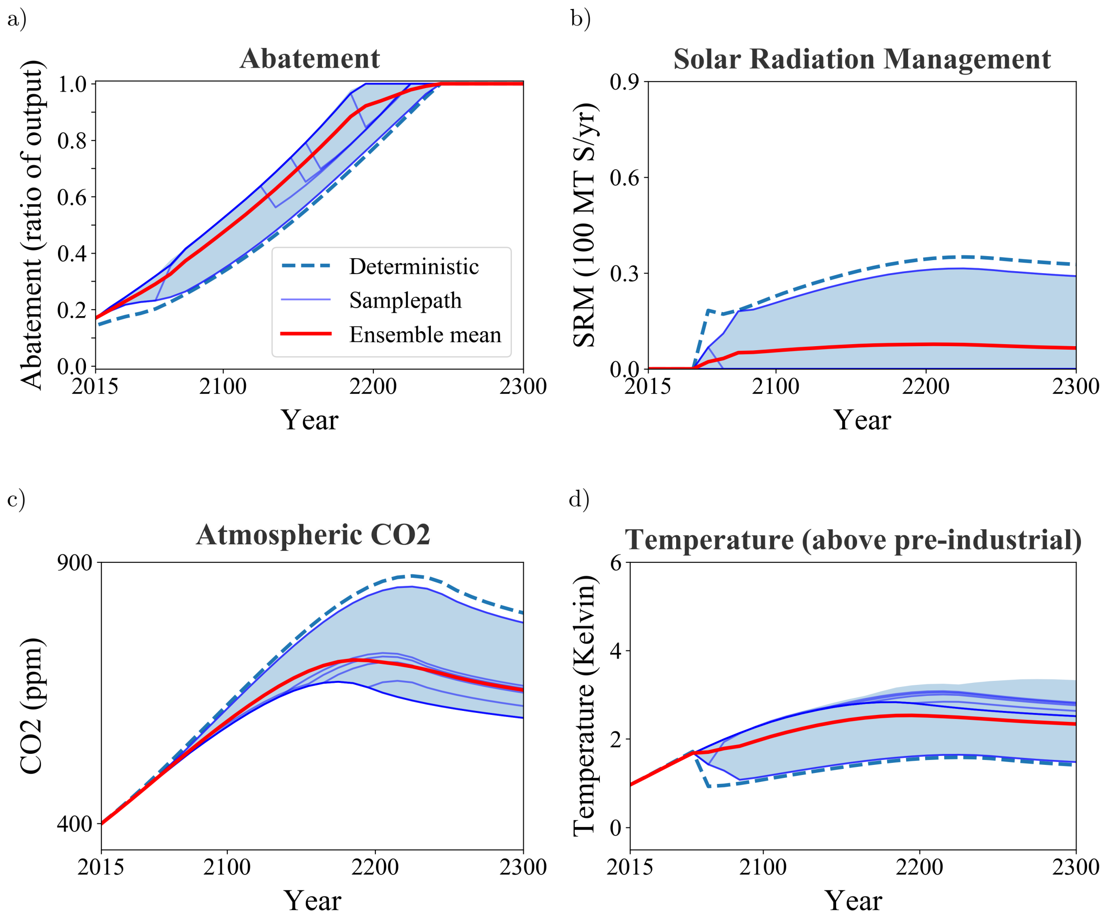

Figure 4. Optimal policy and climate development for the Realistic Storyline scenario. a) Abatement fraction, b) SRM in 100 Mt(S)/yr, c) atmospheric carbon concentration in ppmv, d) global mean temperature change w.r.t pre-industrial. The thin blue lines represent a sample of individual ensemble members, the thick red line the ensemble mean, and the blue shaded area indicates the range of possible values in the whole ensemble. The dashed blue line depicts the results from a deterministic reference case in which SRM becomes available in 2055 certainly and neither SRM failure nor climate tipping occur.

3.3 Realistic Storyline

The previous scenarios were very stylised, in order to isolate the impact of SRM and stochastic elements. However, the actual situation is more complex: Presently SRM is not available and we do not know whether it ever will be; yet we might want to decide now whether to pursue (research and development of) SRM. To address this question, we consider a "Realistic Storyline" scenario, in which we assume that SRM will become possible only in 2055, and only at 30% probability (in the decades before 2055, there is a certain probability each time step that SRM is declared infeasible, e.g. because scientists identify unacceptable environmental risks). We also assume that after 2055, the probability of SRM failure decreases in time, i.e. with ongoing testing~~(see Sect. 2.3). As a coarse representation of damages associated with the termination shock , SRM failure is accompanied by a one-time reduction of the GDP by a factor $1-\psi_{fail} I_S$ where I_S is the injection rate in Mt(S)/yr and ψ_{fail} is given in Table 1~~, and allow for damage associated with a termination shock in case of SRM failure (see Sect. 2.3). Unlike (irreversible) climate tipping, the termination shock is a short-lived phenomenon and is stronger for large SRM.

In those ensemble members where SRM becomes available in 2055, it is used sparingly in the first time step, because the probability of failure is still high and the decision maker wants to limit the termination shock. In later time steps, SRM is used only slightly less than in the Abatement+SRM scenario, peaking at 31.4% rather than 35%. This difference mainly arises because the decision maker wants to reduce the termination shock: If the termination shock damage is omitted from the Realistic Storyline, SRM peaks at 34.7%.

In the first time step (2015), when the decision maker assumes that SRM will become available with 30% probability only, the abatement is $\mu(2015) = 0.17$, only slightly less than in the Abatement-only scenario where $\mu(2015) = 0.18$. For comparison, in a deterministic reference case in which SRM will be available from 2055 certainly, and no SRM failure or tipping occurs, $\mu(2015) = 0.14$ (see Fig. 4). As time progresses until 2055, the ensemble members diverge: If SRM is already banned, abatement increases, but if a time step has passed without a ban, the decision maker becomes more optimistic that SRM will become feasible and abatement becomes less ambitious. In ensemble members where SRM becomes available, 50% abatement is reached 45 years later than in cases where SRM remains impossible. For current policy, however, the most important point is that in 2015 ("now"), the 30% chance of SRM becoming available does not lead to significant reduction in optimal abatement.

On the other hand, the performance ζ of this scenario is 125% (Table 3), significantly higher than for abatement-only. The lowest 10-th percentile performance, ζ_{10} is very similar to the Abatement-only scenario. In the Realistic Storyline, the low-performance members are those in which SRM never becomes available, and the policy (i.e. trajectory of abatement) in these runs is very similar to Abatement-only. However, ζ_{90} is much higher for the Realistic Storyline than for Abatement-only. This measure is dominated by those members in which SRM becomes available. The total climate tipping risk for the Realistic Storyline is 30.1%, compared to 37.8% in the Abatement-only scenario. The SCC for the Realistic Storyline is $37\$/t(C)$, 12% lower than for Abatement-only.

These comparisons between the Realistic Storyline and Abatement-only indicate that the former performs better. ~~In other words,~~ This is because in those cases where SRM does become available, the welfare gain of climate policy is twice as high as in the Abatement-only case. Therefore, a policy maker in 2015 should not dismiss SRM prematurely, but keep the option open (by encouraging research and development). If we are lucky and SRM works well, it can greatly enhance future welfare, whereas if it never becomes feasible, we are not worse off than with abatement-only. (Note, however, that we did not include the possibility of a large-scale SRM test with huge unexpected damage, but assumed careful, well-designed research.) ~~So research in SRM should be continued, but not at the cost of strong efforts on abatement .~~ However, the prospect of possible future SRM should not lead to a significant reduction in abatement efforts at the current stage.

3.4 SRM as 'Climate Insurance'?

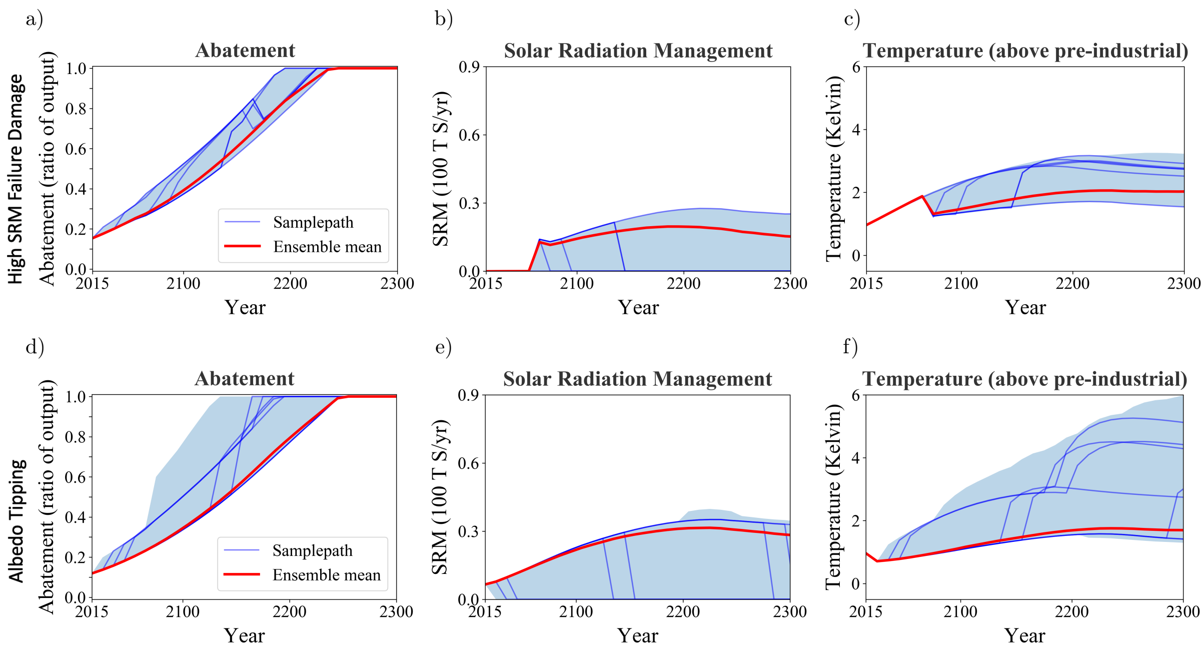

Figure 5. Policy and temperature for the ‘SRM as insurance’ scenarios (see sect. 3.4). The top row shows the scenario with high damage in case of SRM failure, while the bottom row shows the scenario with an albedo tipping point. The left column (a,d) show abatement, the middle one (b,e) SRM, and the right (c,f) warming. The thin blue lines represent a sample of individual ensemble members, the thick red line the ensemble mean, and the blue shaded area indicates the range of possible values in the whole ensemble.

In the previous scenarios, SRM was used in a continuous way as a complement for abatement in order to further reduce global warming, especially when the warming was highest. Here we investigate under which circumstances it can be advisable to use SRM as an ‘insurance’, that is, suddenly increase its use or even voluntarily delay using it at all.

First, we consider a situation in which SRM is very dangerous, and thus unattractive to use unless climate change is also very dangerous. This is achieved by assigning a very high, but one-time, damage to SRM failure, namely reducing capital by a factor $\Omega_K = I_S/(I_S + I_{S0})$ in case of SRM failure. Here I_S is the injection rate in $Mt(S)/yr$ and $I_{S0} = 5Mt(S)/yr$. This means that already at modest injection rates, SRM failure is assumed to cause substantial capital losses. In addition, we increase the likelihood of tipping failure by a factor of 4. Apart from these changes, the scenario is the same as the Abatement+SRM scenario in sect. 3.2. This scenario is not necessarily considered the most likely, but serves as a proof of concept. The result is that SRM is not until the tipping threshold $T = 2K$, threatens to be reached (see fig. 5a-c). When the threshold is reached, SRM is started and somewhat more SRM is applied than strictly necessary to keep below $T + 2K$. This is because in our parametrisation, damage levels off somewhat with increasing injection rate, i.e. if SRM is used at all, then a little extra doesn’t make failure costs that much worse. The temperature is kept below $T = 2K$ throughout, unless SRM fails. Compared to the standard Abatement+SRM case, peak SRM is reduced to $27.6Mt(S)/yr$, i.e. by about 21%, and 50% abatement is reached in

Scenario	Abate 50%	peak SRM	SCC
Abatement-only, standard	2095	/	41
Ab.+SRM, standard	2139	35.0	20
Abatement-only, low rate of pure time preference ($\rho = 0.5\%$)	2068	/	70
Ab.+SRM, low rate of pure time preference ($\rho = 0.5\%$)	2116	31.1	30
Faster decline abatement cost ($\lambda_2 \rightarrow 2; \lambda_3 \rightarrow 0.015$)	2112	29.0	21
Ab.+SRM, less temp. damage, more precip.damage ($\psi_T \rightarrow \psi_T/2$, $\psi_P \rightarrow \psi_P \times 2$)	2143	32.6	17
Ab.+SRM, lower tipping threshold ($T_{tipp} = 2K \rightarrow 1K$)	2139	35.6	21
Ab.+SRM, double damage from tipping ($\Omega = 0.8$)	2136	34.8	20
Ab.+SRM, double climate tipping probability ($\kappa_{tipp} \rightarrow \kappa_{tipp} \times 2$)	2137	34.9	20
Ab.+SRM, quadrupled SRM failure probability ($\kappa_{fail} \rightarrow \kappa_{fail} \times 4$)	2121	34.3	23
Ab.+SRM, double damage from SRM ($\psi_S \rightarrow \psi_S \times 2$)	2133	26.8	22
Ab.+SRM, half damage from SRM ($\psi_S \rightarrow \psi_S/2$)	2143	43.6	20

Table 4. Policy metrics of the sensitivity runs. 'Abate 50%' is the year in which Abatement reaches 50% ($\mu = 0.5$). 'peak SRM' (in $Mt(S)/yr$) is the highest SRM value of the ensemble (over all times and all members) and corresponds to those ensemble members without early SRM failure or climate tipping. 'SCC' is the social cost of carbon in $\$(2005)/t(C)$. All simulations were preformed in the stochastic settings and are either Abatement-only or Abatement+SRM (abbreviated here as Ab.+SRM). The first two cases, labelled 'standard', are repeated from Table 3 for convenience. The sensitivity runs correspond to those discussed in Sect. 3.5.

2127, i.e. 12 years earlier. This experiment shows that the possibility of SRM causing high damage can cause a delay in its use until climate change also becomes very dangerous (tipping threshold reached).

Second, we replace the standard tipping point in Abatement+SRM by the 'albedo' tipping point (see sect. 2.1.4). It is found that if the policy maker can use SRM freely, he does not employ it to such a degree as to stay below $T = T_{alb} = 1.5K$, but takes the (small) chance of crossing the threshold. If this happens, he does increase SRM to counteract the albedo feedback (the 'bump' after 2200 in fig. 5e)). Although the time step for determining policies is 10 years, the albedo feedback is weak enough that no runaway global warming occurs, since with SRM, $T - T_{alb}$ and hence F_{alb} is small. This is why a modest increase suffices to suppress this effect. However, if SRM has failed, temperature is much higher than T_{alb}, increasing both the probability of albedo tipping and the radiative forcing strength if tipping occurs. As in the standard 'Abatement+SRM' scenario, the policy maker increases abatement in case of SRM failure to avoid the tipping point. However, if the albedo tipping occurs after SRM failure, the policy maker increases abatement yet again in order to limit the positive temperature feedback. Nonetheless, the albedo tipping can cause additional warming of more than 2K. A positive climate feedback tipping point can thus lead to enhanced climate policy - SRM or abatement or both - after being triggered, in order to reduce its consequences.

3.5 Sensitivity Analysis

The results of our model substantially depend on the rate of time preference ρ (see Sect. 2.2). In Abatement-only, reducing ρ from the standard value of 1.5% to a lower value of 0.5% will lead to stronger abatement: 50% abatement is reached 27 years earlier (see Table 4). This is expected, as a lower rate of time preference means that the decision maker gives more weight to the welfare of future generations and is more willing to sacrifice present consumption to reduce climate change. The SCC rises from $\$41/t(C)$ to $\$70/t(C)$. Interestingly, abatement also increases in the Abatement+SRM scenario (50% abatement is reached 23 years earlier) when reducing ρ to 0.5%, while the peak SRM (definition: see Table 3) decreases by about 11%. In other words, a decision maker who cares strongly about the future will choose to reduce CO_2 emissions rather than forcing future generations to rely on SRM, which causes damages and might fail. The SCC rises from $\$20/t(C)$ to $\$30/t(C)$.

A potentially important limitation of DICE is that abatement costs are exogenous, whereas in reality one would expect costs to decline with growing employment (learning-by-doing). While fully exploring learning-by-doing is outside the scope of this study, we estimate the sensitivity to abatement costs in a simulation wherein abatement costs decrease more quickly in time and reach a lower value for $t \to \infty$. This is done by putting $\lambda_2 = 1.5, \lambda_3 = 0.015$ in eq. (8), which lowers abatement cost by a factor of about 0.6 after 70 years, compared to the standard scenario. The resulting policy shows a faster abatement by about 30 years, leading to a lower peak in atmospheric carbon (745ppm instead of 870ppm). Peak SRM is reduced to 29Mt(S)/yr, as less SRM is needed if carbon concentrations are lower. Thus the development of abatement cost can significantly affect the need for SRM.

The distribution of the damages between the two major contributors, namely warming and residual climate change, was chosen rather arbitrarily. However, halving ψ_T (warming contribution) and doubling ψ_P (residual contribution) does not qualitatively affect our results. 50% abatement is reached 4 years later in the Abatement+SRM scenario, and SRM peaks at 32.6Mt(S)/year instead of 35.0Mt(S)/year, i.e. the optimal policy still combines a similar abatement with modest SRM. The SCC drops from $\$20/t(C)$ to $\$17/t(C)$. Lowering the tipping threshold from $2K$ to $1K$ leads to a 2% increase in peak SRM, while not affecting abatement. Doubling the damages associated with climate tipping ($\Omega = 0.9 \to \Omega = 0.8$) only accelerates 50% abatement by 3 years in the Abatement+SRM case and the SCC remains at $\$20/t(C)$. Doubling the likelihood of climate tipping (κ_{tipp}) accelerates 50% abatement by 2 years and likewise does not affect SCC. Increasing the failure probability of SRM (κ_{fail}) by a factor of 4, i.e. such that SRM failure occurs in 80% of the ensemble members rather than 20%, increases the SCC only by 15% in the Abatement+SRM scenario, i.e. from $\$20/t(C)$ to $\$23/t(C)$.The reason is that the likelihood of SRM failure in the first decades, which are least discounted, is still fairly small. The peak SRM is reduced only by 2%: As long as SRM is available, it is used despite high failure probability. 50% abatement is reached in 2121, rather than 2138, in the ensemble mean. Doubling the damage associated with SRM (i.e. doubling ψ_S) accelerates 50% abatement by 6 years and the SCC rises from $\$20/t(C)$ to $\$22/t(C)$. The peak SRM is reduced by about 23%, to 26.8Mt(S)/yr. Likewise, halving ψ_S increases peak abatement by 25%. Hence even if SRM is twice (or half) as damaging as assumed in the standard case, the optimal policy still employs modest SRM as complement to abatement.

To summarise, changes in the damage function and/or likelihood of stochastic events do not qualitatively affect the optimal policy in the Abatement+SRM scenario, which consists of a combination of reasonably high abatement (delayed by a few decades w.r.t Abatement-only in the standard settings) and modest SRM.

4 Summary and Discussion

In this paper, we present the first cost-benefit analysis of SRM under uncertainty performed with a rigorous optimisation approach (dynamic programming). From our analysis we draw two conclusions. First, sulphate SRM has the potential to greatly enhance future welfare and should therefore be taken seriously as possible policy option. Second, even if successful, SRM does not replace CO_2 abatement, but complements it. In particular, a policy maker who puts great value on the welfare of future generations (i.e. uses a low rate of pure time preference) will accelerate abatement efforts, which have a long-term benefit, rather than forcing later generations to rely on SRM. Apart from smoothly reducing peak warming, SRM might also have a role to play as emergency measure, e.g. in case of emerging positive warming feedbacks or unforeseen strong climate-induced damages. However, this might be a risky approach if SRM itself is potentially associated with strong damages.

Compared to previous studies (Goes et al., 2011; Moreno-Cruz and Keith, 2013; Heutel et al., 2018), our results are more optimistic about SRM, which seems partly due to the improved methodology we adopted. For instance, demonstrating that welfare is severely impacted if the decision maker makes wrong assumptions on the SRM-related damages (Bahn et al., 2015) is not a consistent cost-benefit analysis. The analysis by Goes et al. (2011) only considers a full replacement of abatement by SRM, rather than a complementary approach. Compared to Heutel et al. (2018), we find a much stronger reduction in the SCC. However, as discussed previously, their model and optimisation method differ in some crucial points from ours. In particular, Heutel et al. (2018) assume that the implementation cost and damage associated with SRM depend on the fraction of CO2-induced radiative forcing that is balanced by SRM - no matter how high the CO2 concentration is - rather than letting costs and damage depend on the amount of sulphur injected. Therefore at high (low) CO2 concentrations, they obtain a much higher (lower) radiative forcing effect from SRM for the same price, which makes SRM more (less) attractive. In their deterministic simulation, they compensate 50% of the peak CO2-induced radiative forcing of $6W/m^2$, which in our model settings would require injection rate of $27Mt(S)/yr$ - about 80% of our peak injection rate of $35Mt(S)/yr$ in the deterministic Abatement+SRM scenario. However, in the first century, Heutel et al. (2018) use considerably less SRM because they overestimate the price by ignoring that much lower injection rates are needed while CO2 concentrations are low. So overall they use too little SRM and therefore end up with higher temperatures (about $2.5K$ peak warming) and a higher SCC.

Our results should not be interpreted as precise policy recommendations to set, say, exact values of the SCC, as our model is too limited to offer more than a qualitative exploration and comparison of simple scenarios. For example, uncertainty in the climate system is limited to one tipping point, while uncertainty in the climate sensitivity is ignored. Our climate model is based on linear response theory, and although this approach captures many climate feedbacks adequately, it does not capture the possible dependence of the response on the background state, e.g. a saturation of carbon sinks (Aengenheyster et al., 2018).

A controversial component in Integrated Assessment Models such as DICE is the quantification of climate damages (Howard, 2014; van den Bergh and Botzen, 2015), which is highly aggregated and based on very limited data. We introduced additional parameters to the damage function by making a plausible, but rather ad-hoc attribution of climate damages to temperature, global precipitation ('residual climate change') and CO_2 concentrations. Also little is known about the size of ecological, let alone economic, damages associated with SRM. Gaining a better understanding of these damages, and those related to climate change, is essential for conducting a meaningful cost-benefit analysis and ultimately determining a climate policy, hence it should be given a high priority.

The ~~economic component of our model also has limitations: it is assumed that a sudden strong increase in abatement is possible after SRM failure, which might be not feasible in reality. Like DICE, our model has an exogenousinnovation and thus ignores~~ abatement sector of DICE also has important limitations. First, technological improvement is exogenous (abatement costs decrease in time at a prescribed rate), rather than including learning-by-doing ~~effects in abatement (and SRM). It also does not capture the fact that the energy transition is partly an investment (e. g. restructuring the energy grid), i. e. abatement costs should reduce once the infrastructure for green energy is set up. These effects may bias our results against abatement.~~ (costs decrease with technology employment). This means that in DICE it is advantageous to wait for the later cost reduction, rather than starting early to bring abatement price down through learning. In addition, DICE assumes that abatement is always costly, whereas in fact, the energy transition might rather be a big investment: Once the infrastructure is installed, green energy might be cost-competitive with fossil fuels. Both effects likely bias our results against early abatement. A faster (still exogenous) decrease in abatement costs was found to lead to faster abatement and reduced peak SRM. Our model does not include negative emission techniques, which might provide an important alternative to SRM. Neither does it include active adaptation. The trade-off between negative emissions, adaptation and SRM would be interesting to study with a more detailed model. Finally, DICE assumes a homogenous economy and a single decision maker. In reality, the damages and benefits of SRM are likely unevenly distributed, with potential for solitary actions and conflict, which was not studied here.

Despite the large scientific and political uncertainties which need to be overcome, we believe that one cannot afford to dismiss SRM at the current stage, as it has the potential to greatly reduce climate risk and enhance future welfare. However, the scientific uncertainties, especially concerning efficiency and damages of SRM, ~~must be quantified, and~~ as well as the extent by which SRM can mitigate damages inflicted by global warming, must be better quantified. For the time being, the uncertain prospect of SRM becoming available should not tempt us to reduce abatement.

Code availability.

Data availability. The code used (described in the Methods section) is available upon request from the corresponding author.

Code and data availability.

Sample availability.

Video supplement.

Appendix A: Solving the GeoDICE model

A1 Terminal function

Unrealistic behaviour occurs in the last time steps of an optimisation problem, because the decisions made do not influence the future anymore (as the future is not simulated). To avoid this problem, we follow Cai et al. (2016) and run the optimisation over 600 years, while only considering the first 400 as actual simulation and the final 200 years as 'terminal function'. During termination, tipping can still occur and SRM can be freely chosen, while abatement is set to 1. Due to discounting, the trajectory after 600 years has little relevance for the optimal policy during the first 400 years. Indeed, prolonging the runs to 800 years had a negligible effect on policies during the first 400 years.

A2 Optimisation method

The social planner problem aims at finding the policy that maximises the expected cumulative discounted utility. To solve this problem in the stochastic setting, we apply dynamic programming (Bellman, 1957). This methodology relies on the concept of the value function to obtain the optimal policy via backward reduction. As our state space is continuous and no analytic solution is available, we are forced to adopt some approximation scheme to represent the value function at each time step. Following Cai et al. (2016), we use a Chebyshev approximation, which is well suited for parallelisation. The Chebyshev polynomial is obtained by solving a small optimisation problem at each of a finite number of regularly spaced Chebyshev approximation nodes. We used a fourth-degree Chebyshev polynomial with five approximation nodes per continuous dimension. In combination with the binary state variables for the tipping point and SRM failure, this results in 312500 approximation nodes per time step. This method is developed and discussed extensively in the work by Cai (2009); Cai et al. (2012a, 2016). For a complete overview we refer the reader to these papers and the references therein. Here we outline the methodological choices specific to the present application: the boundaries used for the domain of the Chebyshev polynomial, and adjustments to the value function approximation to accommodate the asymmetry and non-smoothness of the true value function. Additionally, we examine the accuracy of this methodology when applied in the current setting.

A2.1 Boundaries

In order to define the Chebyshev approximation nodes, we must first set the boundaries of the region of state space in which we are interested. To do this, we calculate three trajectories in the deterministic model: first, the optimal trajectory (obtained by optimising the whole system in all decision variables with standard deterministic optimisation software); second, a 'high-emission' trajectory calculated by setting mitigation and SRM to zero for the whole run; and third, a 'low-emission' trajectory, calculated by setting mitigation to one and SRM to zero for the whole run. We subsequently take as domain boundaries for each variable the minimum and maximum over these three trajectories, with an additional margin of minus, respectively plus 30% of these values. For all experiments, we check that all the sample paths in the ensemble remained well within the boundaries of the domain. For approximation nodes close to the boundaries, it will still be possible to select actions that may bring the system outside the boundaries in the next step. Since a Chebyshev polynomial cannot be extrapolated outside its domain, we first project the state onto the region of interest before evaluating the approximate value function.

A2.2 Value Function Smoothing

In the current setting, directly using a Chebyshev polynomial to approximate the value function gives poor results because the value function exhibits an asymmetry and a non-smoothness that a low-degree Chebyshev polynomial cannot capture. The discontinuity is caused by the fact that in states with positive temperatures, SRM is available to reduce them, while in states with negative temperatures this is impossible: therefore, positive temperature deviations are preferred over negative temperature deviations of equal magnitude. This problem is resolved by allowing 'reverse' SRM, which generates a radiative forcing of the same magnitude but opposite sign as regular SRM. Allowing such actions changes the value of certain states, thus removing the asymmetry. This is a purely mathematical construct (we do not assume such reverse SRM is actually possible): the states with modified values are never reached in actual trajectories, and are only considered in the first place because the domain of the Chebyshev approximation must be a hypercube.

The non-smoothness results from the fact that the tipping point can only be crossed after a certain threshold is reached: this generates a discontinuity in the first derivative of the value function. This is resolved by fitting two separate Chebyshev polynomials to the two parts of the value function.

A2.3 Accuracy

We test the accuracy of our optimisation by comparing the resulting policy in a deterministic setting to the policy obtained by regular non-linear optimisation. The difference in action and trajectory is $< 3\%$, while the difference in the SCC is $< 2\%$. For the scenario in which only abatement is allowed, errors are lower (0.1−1% for actions and SCC, 0.01−0.1% for trajectories), which is in line with the accuracy reported by Cai et al (Cai et al., 2016). Good accuracy in the deterministic setting may not generalise to the stochastic setting when the stochasticity itself introduces issues. To guard against this problem we ensure that the value function approximation fits well to the actual value function samples obtained at each time step.

Author contributions. All authors conceived research. C.E.W. and K.G.H. designed model and scenarios and interpreted results. K.G.H. performed simulations. All authors contributed to writing the paper.

Competing interests. The authors declare no conflict of interest.

Disclaimer.

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