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Earth System Dynamics
Discussions

Interactive comment on "Complementing CO_2 emission reduction by Geoengineering might strongly enhance future welfare" *by* Koen G. Helwegen et al.

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Overall Recommendation: The basic work is interesting and potentially publishable, but in my opinion, there are serious deficiencies in the degree of context included in the text that simply have to be included in a revision of the paper.

General Comments

1. The authors are commended for taking on the task of seeking to do a comparative analysis of the relative merits of a wider set of policy options for responding to human-induced climate change than is traditionally done. This is both appropriate and needed.

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Discussion paper

While I have quite a number of comments about the paper and what more I think is needed, this is not to say that what has been done is a useful advance and I would encourage the authors to keep at this, recognizing that what has been achieved is a starting point and that what will ultimately be needed is a good bit more.

2. Regarding the overall thrust of the article, use of the term “Geoengineering” in the title conveys the impression, at least to me, that both Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM) will be considered. The text actually speaks almost exclusively about Solar Radiation Management, and this is really unfortunate because CDR is really the potential exit strategy for SRM rather than, as in this article, assuming SRM would go on indefinitely. So, one thing missing at the front of the article is a bit of discussion about the various options for responding, which include reducing emissions (normally called mitigation, here called abatement), adaptation, CDR and SRM. And the mitigation or abatement can involve both cutting emissions of long-lived species like CO2 and short-lived species like methane, tropospheric ozone, and black carbon. This article thus only focuses on CO2 mitigation and SRM, and this needs to be more clearly indicated. One could perhaps say that mitigation includes CDR, but then one would also need to be allowing negative net emissions, which is actually something that the IPCC’s recent report ends up on relying on.

3. It is really not made nearly clear enough that what the DICE model calculates is not related to actual climate change impacts, but a “damage function” that is the projected change in the size of GDP. So, while I was expecting the paper to be considering such aspects as impacts on agriculture, forests, ecosystems, coral reefs, biodiversity loss, etc.; the impacts due to sea level rise, extreme weather events, wildfires, etc. The problem with this is that while it is interesting to have an indication of the overall effect on the economy, it is not possible to distinguish the changing share of the economy going to improving general welfare and the share going to recover from disasters, the need to rebuild, the relocation of refugees, and so on. While those familiar with DICE might be aware of this, this paper really needs to be clear on all of this; I just think using

the phrase “damage function” really needs to be clarified. I’d note then that with this construction of the issue, it becomes hard to do more than quite simply represent the tipping point, etc.

4. While the result and conclusion seem plausible, in reading the paper I kept thinking about the shortcomings and limitations of what was being done, even when considering only mitigation/abatement and SRM. Overall, I found it frustrating to only get an overview of the limitations at the end of Section 4 of the article rather than being made aware of the limitations up front and having the limitations then related to the various statements along the way. While I think this paper is an advance, not really clearly indicating the limitations up front and providing some explanation of their potential significance will, I think ,frustrate readers, whereas having the limitation up front and then in Section 2 indicating all that has to be done to get to the advanced point that is reached will better allow appreciation of the challenge posed by this type of analysis, necessary as it is.

5. Another general issue that bothered me was that conclusions were offered on various aspects of the issue (e.g., uncertainties being large) without giving a comparison to anything. Basically, the question posed is whether the world would be better off going through greenhouse gas-induced climate change with or without invoking SRM, so it seems to me that every time some conclusion is proposed about something like uncertainties, the context has to be the other possible option. So, are uncertainties of SRM really large compared to uncertainties of uncontrolled warming (so both with and without abatement), for example. Are uncertainties about having the climate more or less as at present as a result of the equivalent of a human-induced volcanic eruption larger or smaller than the uncertainties of the impacts and results of the climate heading toward a 3-4 C warming (uncertainties considered small enough to justify an international decision to phase out the global fossil fuel energy system later this century)? By not summarizing up front the uncertainties present with respect to projections of global warming of a few degrees C (among which is the issue of tipping pointsâĂŤand there

are likely many, and some are irreversible, like biodiversity loss; some, like the commitment to melting of ice sheets, have long lag times; etc.), there is really no context for making a statement about whether the uncertainties of SRM are important or not. It seems to me that this just has to be provided.

Specific Comments

Page 1, Title: Given the general comment, the word “Geoengineering” in the title needs, in my view to be reconsidered. Perhaps use “Climate Intervention” or something similar so it is clear that CDR is not being considered.

Page 1, line 2: Change to “to lower”. Also, the word “may” seems totally inadequate. First, use of this word is really not helpful in assessments, etc. because it can mean anything from less than 1% to over 99%–basically, anything may happen. I am also surprised that there is any question being raised about impacts being caused (consider the impacts of sea level rise; heat waves; losing the benefits of cold nights to kill infectious disease vectors; landscape shifts that usually occur by over-stressed plants lost rapidly to disease or wildfires and taking many decades to many centuries to become re-established; etc.)âĂŤI know of no scientific assessments that raise any question about there being large, adverse impacts from climate change.

Page 1, lines 3-5: Here is a location to make clear on what basis “gains and damages” are going to be evaluated, what will be compared to what. This sentence says it is evaluating SRM, but is not really what is going to be evaluated global warming with and without both abatement and/or SRM? And here is where to explain that CDR as an exit strategy is not being considered in this analysis, which really has implications for issues of the ethics of imposing SRM on future generations, etc. [In this regard, it needs to be said this is just considering quantifiable economic aspects, and this leaves out a lot of aspects, such as issues like loss of biodiversity, inundation of low-lying islands and associated loss of cultures, and so on.]

Page 1, line 6: IPCC, in all of its volumes, I think forbids use of the word “should” as

policy prescriptive and generally scientists and experts considering limited aspects of issues (e.g., here, only considering economic aspects, and quite limited in that regard). It would be straightforward to simply change “should therefore be” to “merits being”

Page 1, lines 6-7: While true as written, there is inadequate context here as long-term CDR, which could well serve as an exit strategy, is not included. One could perhaps say this is included in Abatement, but this ends up depending on what the temperature target is, a point on which there is some debate.

Page 1, line 9 and lines 12-13: While the Paris Agreement set 2 C or preferably 1.5 C as the target, this was not really a scientific choiceâĂŤit was a political compromise on what was conceived as perhaps possible. Earth’s climatic history suggests that the equilibrium sea level sensitivity may be as large as 15 to 20 meters of sea level rise per degree C change in global average temperature. The time lag for equilibrium to occur is probably something like 1000 years plus or minus a factor of 2 (so 500 to 2000 years), and that is perhaps a one-sigma spread on the low side given how ice calving can occur (see paper by DeConto and Pollard). There are those out there saying the real target to meet the objective of the UNFCCC would more appropriately be less than 0.5 C, or 300 ppm, or something similar, and it would seem to me that this paper would be strengthened if it considered the situation for a range of temperature targets (say 0, 1, and 2 C, for example). On the issue of objective of the Paris Accord, there was no decision included in the agreement, as I understand it from one of the lead negotiators, on whether the 1.5 to 2 C was to be a peak and then the temperature would be reduced, or whether these values would be considered as a new level for the future, as is presumed in the IPCC special 1.5 C report, with the thought being this would meet the UNFCCC objective. As the recent IPCC special report makes clear, staying under 1.5 C would require going to net zero CO2 emissions within a few decades, which the report indicates is technologically possible, but quite unlikely politically and economically. For context, it would really be helpful to indicate what the model suggests would be the costs of a long-term steady state global warming of

1.5 or 2 CâĂŤand in doing that to make very clear what is included and what is not (presumably biodiversity loss, sea level rise, extreme events, etc.).

Page 1, lines 14-16: As to the set of approaches, there is no mention of aggressive cutting of emissions of short-lived species as a way of delaying warming by a couple of decades and no mention of aggressive CDR (or any CDR), and there are those out there hoping that CDR can be really phased up. The sentence here seems to slightly over-simplify the set of options.

Page 2, line 6: So, “associated changes” is all to be said of the impacts from ongoing global warming? Nothing about what this entails and how severe it could be or about what is and is not included in the calculations that are included, to be included, in the modeling here. I’m sorry, but if there is going to be discussion of, as on line 8, that not all changes in precipitation patterns are reversed, it really needs to be said how much the changes in precipitation are without SRM. There is not even a reference here to the impacts of ongoing global warming. In my view, it is essential to be describing the impacts and giving some indication of levels of confidence, etc. Perhaps show the “burning embers” type of diagram to show how serious the impacts are for context in considering whether the SRM shortcomings are significant or not.

Page 2, lines 7-10: Here is another example of not providing a comparison about how important the inadequacy is. For example, how does the supposed difference compare to the departure that would occur without SRM (so with only the CO2 enhancement)âĂŤis the return toward the original perhaps 90%, is the decrease with respect to preindustrial or the CO2 enhanced climate? There are all sorts of SRM injection options yet to be considered such as in amounts and varying by season and latitude yet to be considered, so some tuning of the injection patterns might improve the situation. Are the failures to return to near preindustrial out over the ocean (where there is no impact) or over the land (where there might be)? How does the change compare to the range of natural variability at each locationâĂŤis it significant (e.g., one can get large percentage changes in precipitation over deserts where the absolute amounts are in-

consequential)? I just think the statement here is very inadequate and potentially quite misleading and even pejorative. The real key benefit of SRM might be to reduce sea level rise, but that impact is not even considered. Yes, it is true that ocean acidification is not alleviated, but it needs to be said that the failure to abate rapidly enough will lead to all sorts of impacts, some being irreversible. In my view, this paragraph is just inadequate at presenting what the important situation being addressed is all aboutâĂŤthis is where to be indicating the real significance of the issue, and the text here just does not do it.

Page 2, lines 11-12: There also needs to be a comparison to the cost of abatementâĂŤwhere is that?

Page 2, line 13, first phrase: With respect to “moral issues”, there are also all sort of moral issues without doing SRMâĂŤand these are not mentioned at all. This seems very imbalanced hereâĂŤSRM would presumably be limiting loss of species due to warming and reducing the rate of sea level rise. I do agree that what is said here is representative of some of the media discussions of the issue, but this is supposed to be a paper that really looks at the tradeoffs, but instead does not even talk about the various impacts of global warming and the ethical and other associated issues.

Page 2, lines 13-14: On the impacts of sulphate, I think a subsequent report by the Robock group has showed that the sulphate coming down from the stratosphere is an order of magnitude smaller than ongoing near-surface emissions and that the sulphate coming from the stratosphere is much more spread out than the near-surface emissions, so at a lower loading and so the impacts are very small. In any case, if the paper is going to talk about health impacts, these need to be compared to what would be the case without SRM, and given the IPCC reports on projected health impacts (not even referenced or described here), the overall health effects would arguably be quite small as compared to 2 to 3 C warming scenarios. It is simply essential in the type of analysis this paper is doing to make comparisons and provide context, so considering global warming with and without SRM and not just talking about SRM impacts in isolation.

Page 2, lines 15-17: Yes, perhaps, but you did say the cost of SRM is virtually trivial, so how about considering whether some other nation or set of nations might take it up if the costs would be so large of the discontinuance. Now, a critical issue associated with this is also if one is proposing that SRM go on forever (though the approach here discounts long-term impacts away) versus there being CDR that could provide an exit strategy for SRM. The really serious governance failure is the one going on in governments not carrying out adequate abatement, which is far more costly and so much more likely, it seems to me, to continue to be done too slowly. For a balanced presentation, context is needed here providing an indication of the relative likelihood of success and failure of each approach (i.e., abatement and SRM). I would also suggest that this paragraph does not provide adequate and balanced context for the comparison that is being carried out in this paper.

Page 2, lines 18-19: First, this is really a comparative analysis of SRM and abatement, not just of SRM. Second, try to avoid the word "should." On the issue of "tipping behavior", some explanation is needed; namely that there are likely multiple tipping points, that some may be irreversible, that some have lag times, and so onâĂŤbasically, the situation is quite complex.

Page 2, lines 19-20: On the potential for failures of SRM, there is a potential for inadequacy, especially as the temperature to be offset rises to above 2 C, for exampleâĂŤit is a bit hard to see how there could be a possibility of insufficiency for lower temperature increases given that volcanic eruptions do cool the climate. On the issue of the potential for damaging side-effects, again, there is no context hereâĂŤso this needs to be compared to the type of damaging impacts that would occur without any SRM. This is not an analysis of doing SRM or notâĂŤif that were the case, the evaluation would be quite different. This is, however, an analysis of global warming with and without abatement and/or SRMâĂŤso global warming is the underlying baseline, and that will have very serious consequences (after all, they are seen as severe enough the nations of the world have been convinced to work to forego any use at all of fossil fuels).

Page 2, lines 20-21: On use of the DICE model, it seems to me that some explanation is needed. What it focuses on, as I understand it, is GDP(or equivalent) without really subdividing whether the expenditures are going toward improving public welfare or are going for costs to adjust and recover from disasters [in one early study of the Social Cost of Carbon, the early DICE model , so seemingly the one used here, apparently calculated that a 10 C global warming, something never experienced on Earth, would only lead to a 30% or so hit on GDP; well, perhaps, but what share of the economy would not be devoted to improving health and welfare]. In my view, the authors need to do some explaining of what "optimal" means in the context of the study being done. There is also the need to indicate the time step and how extreme weather, etc., which typically causes the most damaging impacts, are or are not treated (the random variation, for example).

Page 2, line 31: Is DSICE updated at all from Nordhaus (1992) other than to allow statistical treatment? So, are climate impacts also statistically treated for CO2, or just for SRM?

Page 3, Table 1: Given the page offers extra width, I'd suggest a bit more explanatory phrase under the "Meaning" column. On the various specifics a. What does the value for CO2 forcing mean? Presumably it is not for CO2 doubling as is too high for that. b. What is the basis for the sulphate scaling and how are the three variables different? c. How are b1 and b2 differentâĂŤthere is room to explain? d. How are the two taus differentâĂŤexpand on meaning? e. On pC, why is the value negative? Total precipitation goes up with CO2. f. On economic damage from CO2 concentration, from warming, from precipitation change, from SRM and from SRM, the units all seem strange. Where is the unit for economic value? g. On the implementation cost of SRM, this value seems to be a good bit higher than page 2, line 11. h. Is the rate of capital appreciation, is this the discount rate?

Page 4, lines 2-8: There is no mention of tropospheric ozone, which is responsible for about as much forcing as methane. On line 3, why does this say "industrial aerosol"

given there are other sources as well (so there are really “aerosols”)?

Page 5, line 5: Why does this say “industrial processes”? At least in some locations this would mean emissions from industry and not include most transportation, home heating, etc. Perhaps say instead “combustion of fossil fuels”.

Page 5, line 6: So, the analysis does not consider any reduction in the rate of C loss from the biosphere? This seems rather strange, given the attitude it will take to do abatement, etc.

Page 5, lines 19-20: Does this mean that one cannot go below a CO2 concentration of something like 400 ppm, so CDR to take the concentration back toward 300 ppm cannot be considered?

Page 6, lines 11-13: This explanation needs to be re-phrased. Over the ocean, the atmosphere does not warm faster than the oceanâĂŤthe atmosphere has a negative balance and so is warmed by convection up to match the warming of the ocean, which is slow due to its heat capacity. Over land, with a reduced surface heat capacity, warming there can be a bit faster, so the global average temperature of the system can lead the ocean by a bit. Despite this, global precipitation goes up with overall global warming, not down.

Page 6, lines 13-15: I don’t understand what is meant that “For SRM, the instantaneous response is weaker.” The temperature goes down quite quickly after a volcanic eruptionâĂŤthe reasoning here really does need to be explained more clearly. And how rising CO2 leads to less precipitation is just not clear given precipitation goes up with global warming. Now, it is true that evaporation goes up as well, so perhaps this is referring to available soil moisture, but I am perplexed by explanation here.

Page 6, lines 16-17: What is a bit confusing here is why there is not, perhaps, a non-linear relationship of impacts from changes in precipitation. Basically, there is natural variability and the systems tend to respond, and impacts occur as the changes become

larger, etc.

Page 6, lines 19-21: So, contrary what I said earlier, does this man that damages don't count in the GDP, or is this the effect of there just being less economic activity and responses to other types of damage are included in the GDP? It seems to me here that some clarification is neededâĂŤwhat seems this is talking about is not damage and impacts on people, but only reduction in economic activity. So, if a wildfire wipes out a town and then insurance pays to rebuild it, there is an increase in local, at least, economic activity even though there have been disastrous consequences. Calling this a "damage function" seems rather misleading to me.

Page 6, lines 22-24: On tipping points, this notion that economic impact could only drop to 0.9 seems rather optimistic. Roughly a half dozen countries provide something like 90% of the grain exports in the world that supply of order a 100 nations; we've experienced mild crop failures in 1 of the half dozen nations at a time and seen significant changesâĂŤas extremes increase, the likelihood of failures in 2 or more of the exporting nations is likely to go up sharply [Hansen et al. have analyzed observational data of hot summers in Northern Hemisphere land areas, and since the mid-20th century, what were three-sigma warm summers (he divided the land areas into 5-degree squares, so roughly one in a 1000 event) are now occurring over 10% of the time, a factor of over a 100 increase. A severe food crisis would pull substantial funds out of the rest of the economy and the heavily leveraged economy could come crashing down far more than the banking crisis. And then there is what would happen if a large ice stream really collapsed and cause a meter or more sea level rise in less than a decade; the flooding and refugee crisis would be enormous. The real challenge here is that the world does not live based on slow and steady change, but from not much happening to some extreme, and extreme conditions are becoming much more likely.

Page 6, line 26: Why is SRM cost linear? Would there not be savings as more and more is needed (offset perhaps by effectiveness decreasing as get higher and higherâĂŤbut effectiveness is separately treated)?

Page 6, lines 29-30: I'd suggest that the goal will be to avoid taking the oxygen molecules from the ground to the stratosphere as there is plenty of oxygen up there. So, what is taken up might be pure S or H2S, etc. rather than taking SO2 from the surface to the stratosphere.

Page 7, Figure 1: I don't understand why CO2 is shown to decrease precipitation? Yes, instantly there is a slight stabilization of the troposphere, but that leaves the heat to warm the ocean, and ultimately the increase in the CO2 concentration leads to an increase in global precipitation. What would seem to be needed is to have arrows of different breadth as ultimately the precipitation amount goes up. On the 30% effect of precipitation on economic damage, I guess that might be viable if there is an understanding that the rain is coming down more in extreme events (and it might be useful to mention this).

Page 7, caption to Figure 1: Where does the last sentence of the caption come from? Overall, the injections are strongly limiting warming and so greatly reducing impacts (assuming warming causes significant impact) and one might say one would only count 80% of this, or does this mean that offsetting 2.5K has an overall negative impact. I'm confused.

Page 7, line 4: So, this equation does not seem to account for sea level riseâĂŤhow is this accounted for or is it not? Are any impacts related to environmental refugees considered and the disruptions that would result? Do the impacts go down over time based on an assumption that adaptation will occur?

Page 7, line 5: What are the consequences of the CO2 concentration changeâĂŤis this an indication of ocean acidification? Is it the loss of nutrients in food crops from the higher CO2 concentration? Etc. It would help to give an indication.

Page 7, lines 6-7: On this issue of both positive and negative precipitation changes causing negative economic impacts, so what is being compared to whatâĂŤwhat is the baseline? So, if SRM leads to much smaller precipitation changes than does global

warming without SRM that its economic costs are less than for CO2, or is the cost based on the departure from the elevated amount of rainfall from global warming?

Page 8, line 6: Is the sea level impact here referring to storm surges? If so, that is not really a complete representation of the consequences of sea level rise given the size of the temperature increase that is being consideredâĂŤthe impact costs of sea level rise will be far, far more than linear.

Page 8, line 15: As previously noted, a really serious but plausible extreme could, it would seem, have much more than a 10% effect. What is the basis for making this the limit instead of having some relationship allowing for smaller likelihoods of much larger economic effects, etc.

Page 8, line 18: How is it that it is presumed that there is zero chance of a tipping point for global warming less than 2 K? This seems very misleading. The Arctic is going to really suffer with global average warming less than 2 K, especially given all that is happening at global warming of 1 K. It would be perfectly impossible to have a food crisis at well below 2 K. And most important, warming of less than 2 K seems quite likely to have started destabilization of several of the Greenland and Antarctic ice streams that would cause long and irreversible sea level rise. I just don't think the 2 K value is justified even though I recall that DICE might have had the assumption of relatively small impacts for less than 2 K?

Page 8, lines 21-22: I'd suggest that the likelihood of unforeseen dangers from SRM keeping the global average temperature near where it is or was in the recent past are far less than the likelihood of surprising outcomes as the global average temperature rises to 2 K and above, a climate regime we are not at all familiar with (and as the relatively greater responsiveness of the Greenland and Antarctic ice sheets are showing compared to what IPCC assessments through the Fourth assessment were indicating).

Page 8, lines 24-25: With SRM failure, does not the temperature go up and that would be expected to lead to very serious impacts, due to both the rate and magnitude. So, is

this sentence just saying there is nothing other than this? If rapid warming rather than gradual warming is the result, would not there be an additional consequence of SRM failing. The abstract hints at this resultâĂŤso how come it is not part of the calculation here.

Page 8, lines 26-27: I'd suggest making much more of this presumption that the impacts are expected to be the same for everyone in the world, and so there is no consideration of especially vulnerable populations even though virtually all assessments note that the impacts will not be felt evenly. It would seem this needs mention and a reference.

Page 9, lines 1-6: So, sea level rise impacts really don't matter, nor do long term impacts of ocean acidification on the marine food chain? This seems quite perverse, making it such that initiating very significant sea level rise ahead ends up having virtually no present valueâĂŤno counting of flooding low lying island nations and low-lying coastal areas, no treatment of loss of biodiversity, and so on. As noted in the general comments, I'm very troubled by how the implications of various of the assumptions are just not discussedâĂŤthis just has to be done to show the limits of the study so future studies will be done better. It seems to me that the way to do this calculation would be to have some share of the impacts with a discount rate and some not as there is simply no way to replace the Amazon rainforest, etc.

Page 9, lines 20-21: It would be best to avoid use of the words "may" and "might" and say something like "a thorough analysis and evaluation would consider not only the ensemble mean, but also the full range of possible values."

Page 9, line 29: Is there not a fourth scenario of doing nothing at all? That would seem to be needed to get a sense of how serious unaddressed climate change would be.

Page 10, line 6: How is that it will take until 2055 to even start SRM? That seems far too long. Indeed, it would seem that waiting until the global average temperature has risen to over 2 K before doing anything. Ideally, it would seem, one would start

ASAP and do SRM at a slowly increasing amount to avoid the irreversible impacts of going up to over 2 K before acting. Unfortunately, however, the analysis here seems to not really treat irreversible impacts and situations where long-term impacts with a very large hysteresis like major loss of ice from the Greenland and Antarctic ice sheets are initiated. Also, assuming only 30% probabilityâĂŤis that due to technological issues or governance issues, etc.? I just do not think the assumptions here are particularly plausible.

Page 10, lines 14-15: So, is the demand for electricity for air conditioning reduced with SRM? A study I know of says this is a really large termâĂŤnamely that SRM slows the rate of global emissions of CO2.

Page 10, line 16: Is there really enough carbon around to go to 2000 ppm of CO2, especially at the rate shown so that it would be continuing to increase beyond that? This seems a very extreme base case to be running. I would very much like to understand the impacts that would be generated by the real baseline case of CO2 growth with no abatement and no SRM.

Page 10, line 19: What is the comparison being made here. Is this saying that the damage of injection of sulphate is higher than the impacts, which would presumably near zero as there is no temperature increase? The real comparison that needs to be made is the impact cost of sulphate to the impacts that would be resulting at that time from global warming of 5.4 K in 2400; with that level of warming, virtually all of the ice sheets would be melted and sea level would be up by 50 meters or so, and the damage due to that would, I would think, be far, far larger than the impacts of the sulphate injection (well, GDP might still be viable, but it would all be going to relocating the global population and not to enhancing human welfare). And then global agriculture would be very seriously disrupted and all global ecosystems would have been destroyed. I just do not think this sentence has been at all justified.

Page 11, Figure 2: I don't understand the SRM (lower right) figure. If the assumption is

that SRM cannot begin until 2055, how come this graph shows the green line jogging down right after 2015. Is this saying we are not now doing what makes sense in terms of abatementâĂŤif so, this could usefully be mentioned. With respect to the upper right diagram, why is this the only figure that starts in 2005 instead of 2015?

Page 12, Table 3: The value of the SCC looks very lowâĂŤand it is not clear when this value applies (is this a starting or ending value?). If the SCC is really this low, it really seems that the estimated impacts are far less than is being discussed in international assessments (and this was a characteristic, as I recall, of the original DICE model). I'd also like to better understand how the abatement costs are calculatedâĂŤwith solar and wind costs already ending up lower than coal for electricity and solid state batteries coming along that will greatly reduce the cost of converting the transportation sector, is the abatement cost taking into account the rate of technological change going on and that would be encouraged by a rising SCC? This actually raises the question if there has been any verification of the DICE model for some period, say, 1970 to 2020 or something. It would be nice to understand what the confidence level for the DICE model is.

Page 12, lines 14-15: This is a very strange way to treating tipping points. There are likely multiple ones and the idea that going to greater and greater warming would be more acceptable after passing one tipping point seems to be a serious shortcoming of this model.

Page 13, Figure 3: So, figures g, h, i show a tremendous slippery slope problem (which is eventually discussed on page 14, lines 25-30). This is, I would presume a result of fossil fuels having a lower cost than the alternatives. Given that the crossover to less expensive renewables is occurring now for electricity generation and I would argue will happen within two decades for electric vehicles (once solid-state batteries replace lithium batteries), so why in the world would people go back to fossil fuels as SRM comes along somewhat later. I just do not understand what is leading to this unless technological improvement is not occurring.

Page 14, line 7: This is really bizarre that SRM is not allowed to start until T equal 2 K. I presume this is because of the limit imposed that SRM cannot start before 2055. One would think that starting earlier and with less intensity would make the most sense and would avoid irreversible losses to ice on land, biodiversity, extreme weather impacts, etc. out until that date. So, the discussion here is all because of an assumption made on when SRM can be started. Such presumptions need to be stated and then stated again when it determines a result.

Page 14, line 16: This notion of SRM failure is quite strange.

Page 15, Figure 4: While the IPCC 1.5 report does presume that the Paris temperature goals meant these could be considered a new, non-dangerous, steady state, paleoclimatic data simply do not support this proposition unless one is willing to tolerate of order 50 meters of sea level rise. Also delaying SRM until 2055 leads to some impacts that one would like to avoid by starting SRM earlier. Allowing the CO2 concentration to go so high seems likely to lead to an unacceptable level of ocean acidification, especially for coral atolls, and quite possibly global shellfish productivity and more. It seems to me the economic damage function used does not come close to representing the actual impacts that will be occurring. It seems pretty clear to me that using the DICE model avoids getting at the actual impacts on the environment and society, and so global human and environmental welfare as opposed to just the drop in GNP. Again, it is absolutely essential that the shortcomings of this analysis be indicated, even though the ultimate conclusion of doing everything one can makes the most sense.

Page 16 line 1: Imposing 2055 and 30% probability is quite limiting. It would be interesting to see a sensitivity study on these values, but since the damage function is only related to total economic activity and does not treat irreversible losses or initiating long term ice sheet loss, etc., probably a small effect. Very clearly, the limitations imposed by the use of the DICE damage function has a very limiting effect on the analysis here.

Page 16, lines 2-3: In saying “identify unacceptable environmental risks”, there needs

to be contextâĂŤso compared to what would happen without SRM and with only abatement, etc. This establishment of some absolute side effect that is unacceptable seems inappropriate to meâĂŤone has to provide context for the decision. Policymakers make decisions on relative likelihood or balance, and so will want the comparison.

Page 16, lines 5-6: So, this sort of assumes, one failure and never use SRM again, even though the impacts of very large warming would be very significant. So, it needs to be stated this is presumably an irrevocable decision despite other impacts.

Page 16, line 17: So, most of the abatement going on will be a result of a technological advance. Once a technological advance becomes economical, it will likely go forward independent of whether SRM is coming or not. I guess the decision-maker could reduce a subsidy and that might slow a transition, though this really means one is not allowing at all for movements, even though movements would seem to be a major factor in transitions rather than just economics. Another limitation that needs to be restated, etc.

Page 16, line 26: I think it needs to be explained why the SCC is so much lower here than has been estimated in other studies. With the international leaders seeing 2 K as essentially unacceptable, the Shadow Price of Carbon (so the value to keep below 2K) is pretty clearly much greater than the SCC valueâĂŤindeed, the SCC value here seems much lower than is generally being discussed. I think the authors need to indicate the reasons that the SCC here is so low compared to what has been shown in other studies of the SCC.

Page 16, line 31-33: In that SRM is based on physical mechanisms (so no chance of a runaway effect as could happen were there a biological factor being introduced in the environment) and for which there is a pretty close natural analog (namely volcanic eruptions), the likelihood of “huge unexpected damage” would seem to be pretty smallâĂŤand in mentioning this here, there again needs to be context provided, so huge compared to what? On the need to continue SRM research, this conclusion would

seem to merit much greater prominence.

Page 17, line 1: Generally, I like the Sensitivity Analysis section. I would be interested in seeing a sensitivity study on the rate of technological advancement.

Page 17, line 9: I am confused; SRM will surely have greater benefits than negative impacts, otherwise why would it be continued? Yes, there may be larger or lesser benefits, but how is it that SRM will cause net damages [I guess, if one counts only dollars using the specified discount rate, one may get a negative consequence if SRM is kept going for reasons other than its effect on the overall economy (e.g., to preserve biodiversity that is not in the damage function)].

Page 18, line 3: What about also halving the damage associated with SRM.

Page 18, lines 21 to Page 19, line 3: This is just far too far back in the document and far too limited to be an adequate disclosure to the reader of the shortcomings and limitations of this study. Yes, it is a start, and the conclusion may be robust, but there is much, much more to be done and far too many limitations and failures to enumerate the shortcomings. Such disclosures need to be made clear up front, mentioned throughout, and included and evaluated in the summary and discussion section.

Page 19, lines 5-7: Putting all the emphasis on uncertainties relating to SRM is just not a balanced conclusion; consider issues of the base calculation not treating sea level rise, irreversible losses like biodiversity, and so onâĂŤthe DICE damage function is just not adequate for the study undertaken except in the most general sense.

Page 20, line 30 and page 21, line 1: Just a comment that it is quite easy to warm the planetâĂŤjust add some CFCs, or HFCs if you want to have a shorter lifetime. Geoengineering warming is far easier than intervening to cool the system. There are issues of time constants, etc. but avoiding an ice age would be far easier than creating one.

Technical Comments

Page 1, line 1: Suggest changing “in spite of” to “caused by”

Page 1, line 8: Clearer if change “can” to “can only”

Page 1, line 14: While Crutzen (2006) did get the recent discussion going, the way the text reads it is a bit hard to understand how a 2006 reference is a response to the Paris Accord, as the text on lines 12-14 seems to convey.

Page 1, line 20: I’d suggest changing to “stratosphere, which would, like an ongoing volcanic eruption, increase”

Page 1, line 21: The reference to “Thomson et al.” has a different spelling in the references.

Page 2, line 4: “sufficiently strong forcing can be achieved” to do whatâĂŤgo over 2 W/m2; if so by how much.

Page 2, lines 23-24: In references, “MorenoCruz” is hyphenated. On line 24, “which” to “that”

Page 8, line 2: Not clear what this is referring to, and why is the effect here 20% and not the 10% in Figure 1?

Page 10, line 18: “very high injection rates”âĂŤthat you are referring to injections of sulphate (actually, of course, earlier the assumption was that it was SO2 being injected, not sulphate).

Page 12, line 10: Change to “individual”

Page 13, Figure 3. Why does the upper left diagram go to 2400 instead of 2300 like all the other figures? On figure j, k, i, I’d suggest having the same vertical span for all three figures so one can more easily compare results. For figures g, h, I, the word “Atmospheric” is misspelled.

Page 14, line 8: I don’t understand what a performance of “181%” means? What is

being divided by what?

Page 14, line 9: The graph only goes to 2300, not to 2415? Going out that far seems very questionable. What one really wants to do is start SRM early and then have CDR come on so it can be phased out.

Page 20, lines 21-22: I don't understand the meaning of the phrase after "with"

Page 22 ff. on references: a. In Cai, spelling is "Stanford" b. In Cai et al., why is article title in title case? c. In Keller et al., what is "ncomms"? d. Stowe et al, is out of alphabetical order and initials of first author need to go after the name

Please also note the supplement to this comment:
https://www.earth-syst-dynam-discuss.net/esd-2019-5/esd-2019-5-RC1-supplement.pdf

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Interactive comment on Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2019-5, 2019.

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Discussion paper