Reviewer 1

We thank the reviewer for the helpful comments. The reviewers comments are in grey, whilst our responses are in black and italicised.

The paper “The interaction of solar radiation modification with Earth System Tipping Elements” by Futerman et al., explores the current state of the literature of the effects of solar radiation modification (SRM) on climate tipping elements. This is a very timely review that should indeed be carried out in order to inform future research on SRM; therefore, I believe that the authors have a very good reasoning for their review article at this critical point in time. While I can see the time and effort that the authors put in this review article, I found the rationale of the article difficult to grasp and think that several changes are necessary before this article can be considered for publication in Earth System Dynamics. I apologize for my critical feedback and I hope the authors will find the comments below helpful for their decision on how to proceed.

We thank reviewer 1 for these helpful comments. As we discuss in response to the key points, we agree with this reviewer that more clarity needs to be provided with regards to the rationale, and we believe that the edits we have made and the replies here should help with this clarity.

Key points:

Streamlining of the article: Throughout the article, each of the tipping elements is split up into four parts: (i) Current state of the tipping element; (ii) Drivers and Feedbacks; (iii) Impacts of SRM; (iv) Further research. While I think that the core of the paper is in (iii), I do not think that another review on the current state of the tipping elements as well as drivers and feedbacks is necessary (not the main topic of this paper, is it?) or helpful (the current state of the tipping elements is done in the global tipping points report and the many other papers of this special issue). Therefore, I suggest to strongly cut those parts (maybe put the long version in an SI if the authors would like to keep this information). For instance, the section on Mountain Glaciers (2.3) had a good balance between the subsections in my view.

This is not to say that I didn’t find this information valuable and interesting to read, but it distracts from the main purpose of this article (SRM) in my view.

Rationale of the article: The above (my point 1) is partially reflected in the abstract where the authors state that they review the literature on SRM but given that there is not a lot of literature they state that additionally a review of the current state of tipping elements as well as their drivers and feedbacks was carried out. I think this rationale is invalid and needs to be sharpened. In my view, a review on SRM on tipping elements is warranted even if the current state of literature is still immature and sparse in some places. This should be reflected in the abstract and the text overall. It can, however, not be an excuse to add only partially related parts to a paper because literature evidence of a certain aspect is weak.

We agree with this reviewer that this piece should be cut down, and we have in parts cut down particularly part i each section, and moved some of this to the supplement. However, we (agreeing with Reviewer 2) believe those earlier parts are still useful, although we have clarified our rationale for doing this in response to this comment. Our revised rational may be stated as follows:

We review the existing literature of the impact of SRM on various tipping elements. However, because the evidence that attempts to give direct indications of this (ie explicit modelling studies) are exceptionally sparse, we attempt to make a qualitative assessment of the possible impact of SRM on these tipping elements using the literature of the impact of SRM on what has been identified as key drivers and dynamics of the tipping elements. To do this, we first review the possible drivers and dynamics to establish what parts of the earth system we need to assess the impact of SRM on (eg Amazon drying, North Atlantic Surface Ocean Temperature etc). Then, using that information, we come up with first order, evidence backed indications of what one would expect the impact of SRM to be on the tipping element by assessing its impact on these drivers, and the possibility of reversal (once tipping has started but not concluded) by its impact on the dynamics. For some tipping elements, overall judgement is feasible, as SRM may push all the important drivers in the same direction with reasonable uncertainty (for example those elements that are mainly temperature driven). For others, the impact of SRM may be different on different drivers, so either no overall judgement can be made, or a judgement with a large range of resultant impacts and a high range of uncertainty (ie those that are primarily precipitation driven) This is why part ii (as identified by the reviewer) of each section is necessary; without reviewing the drivers and dynamics, this method that attempts to use our fundamental understanding of the tipping elements to establish the impact of SRM is not possible. This is also now reflected in the table, with the impact of SRM on each individual driver stated, as well as the overall judgement; this should further clarify the rationale.

Given this justification, whilst we disagree with the reviewer that part ii is unnecessary, we agree that part i can be cut down. We have done this, although still have kept some information in to allow readers with perhaps less context on tipping (eg those who have come from the SRM community) to understand at least what each tipping element refers to and why it may be significant. We have done this as we hope this paper will be useful to a wide range of readers from different scientific communities who may be interested in the topic.

Main results/Table 1: I think this is the main outcome of the paper and I like it very much (with some smaller suggestions below). This table should be placed in the beginning and then elaborated in the specific sections. This gives the reader a clear picture of the main results early on in the article instead of after 47 pages of text – I believe this table is also not announced before so that the reader could anticipate. I also strongly recommend to add at least one further figure that graphically represents the table, e.g. on a world map populated with the tipping elements and their reaction to SRM.

We fully agree on both of these points. We have moved the table to the introduction, and have created a figure showing a world map and the impacts of SRM on the tipping elements. This figure shows our overall judgement of the impacts of SRM on the

prevention of tipping in each of the tipping elements (this is decomposed by driver in the table) as well as a sense of our uncertainty in this judgement.

Overall, I believe that the manuscript would profit a lot from a clearer focus on SRM.

We hope the increased clarification of our method in particular should help this, allowing the explanations of the drivers and dynamics to be seen as only there in service of understanding the impact of SRM on the tipping elements. The foregrounding of the table in the abstract (in response to your helpful suggestion), should further show this to the reader. We have also added in discussion of the impacts of SRM on every driver we mention in the table within the appropriate sections, further increasing the focus on SRM. The cutting of much of part i of each tipping element should also further enhance the focus on SRM.

Some concrete points below.

Major points:

I find that section 1.3 (Solar Radiation Modification and Tipping Elements) could be streamlined strongly.

We have edited this section to attempt to streamline it, as well as to explain what we mean by various terms of the impact of SRM (ie 'prevent tipping' 'reverse tipping'). We have added a figure to further aid with clarity in this section; this figure also may aid in further clarifying the justification discussed above.

While figure 1 is illustrative, I am unsure whether this is really useful in this manuscript because it is not a result from this paper but a reproduction.

We feel figure 1 is useful to the reader to understand the various feedback processes that can allow for land ice tipping to happen. If you accept that, under our newly clarified rationale, understanding the drivers and dynamics is key to understanding the plausible impact of SRM, then we think this figure may still be useful to the reader.

In my view, this is similar for figure 2 as long as there are no studies that discuss how SRM directly alters Atlantic Ocean circulations; if there are, please add them to the figure.

We have edited figure 2 to include the impact of SRM on the Atlantic Ocean circulations in the figure.

Figure 3 is a general figure of S-shapes that allows for different types of tipping (forcing, noise, rate, …). As such, this figure is not specific to the AMOC and should either be removed or moved up to the introduction. It may actually be a good figure to discuss threshold-free feedbacks as opposed to different types of tipping in the introduction.

An updated version of this figure including threshold-free feedbacks has been moved to the introduction.

Page 12, l 322-346: Can be strongly shortened in my opinion. In particular if there are not many studies that discuss SRM, then this should be stated, and additional CDR

studies (e.g. Garbe et al., 2020) should be kept very brief as this is not the main contribution of the paper as I understand.

This has now been shortened.

Pages 32-35: The impact of SRM on ecological systems in general: As opposed to the other sections which are excellently referenced, this section is not. Further, my overall feeling is that this section can be condensed to around 20-35% of text lengths.

This section has been cut down considerably.

Section 5.2: Dipterocarp Forests: This is not a global tipping element. Why is it discussed in this manuscript? Do the authors suggest that it should be considered a climate tipping element because it is relevant on the global scale? For me, it sounds regionally very relevant but more like a super-regional regime shift rather than a global tipping element (e.g. see Rocha et al., 2018, Science: 1126/science.aat7850). Maybe this section can be moved to the SI or removed.

The section on Dipterocarp forests has been moved to the Supplement and some of the text was clarified.

Section 5.5: Indian subcontinent biodiversity hotspots: It is unclear to me why this section is included because (i) it is not a climate tipping element and (ii) there are also hotspots of biodiversity in Africa, Indonesia and particular in South America. Therefore, I suggest to move this section in the SI of the paper or remove it.

We focus in the biosphere section on tipping elements (and their tipping points) in ecological systems that could well qualify as global or regional impact climate tipping elements (or we called Earth system tipping elements). We have attempted to clarify that what we mean by ecological tipping elements may be different from other climate tipping elements covered in other sections in this paper (in section 1.1: " In ecological systems, the concept of tipping elements may be somewhat different, with tipping behaviour is not only seen for large, complex systems, but also on the level of species, and events leading to species extinction can be considered a tipping point. "), which may involve feedbacks to climate, or not, or the feedbacks to climate may not be well understood. We agree that this is not a climate element, and while we agree that (fortunately) there are biodiversity centres elsewhere, this system (now called "the Himalaya-to-Sundarbans (HTS) Hydro-ecological System" in the revised section) is unusual and highly relevant to the discussion here. This comment was critically helpful in allowing us to realise that we needed to clarify what is unique about this system and why it may have the potential to qualify as an Earth System tipping element according to existing definitions. According to Lenton et al. 2008 and Armstrong McKay et al. 2022, climate tipping elements should be "at least subcontinental in scale (of the order of 1000 km, i.e., ~1 M km2) and could pass a tipping point as a result of actions this century" and they "either (i) contribute significantly to the overall mode of operation of the Earth system (such that tipping them modifies the overall state of the whole system), (ii) contribute significantly to human welfare (such that tipping them affects >~100 million people), or (iii) have great value in themselves as a unique feature of the Earth system", and "Global core tipping elements must meet criterion (i) whereas regional impact tipping elements must meet criterion (ii) or (iii) but not (i)."

From these definitions, we believe the Himalaya-to-Sundarbans (HTS) hydro-ecological system may be well qualified as a regional impact tipping element as it meets both criterion (ii) and (iii) as well as the subcontinental scale. If low-latitude coral reefs are considered "regional impact tipping elements" as explained in Armstrong McKay et al. 2022: "Given regionally synchronized tipping dynamics with significant human but indirect climate impacts, we categorize warm-water coral reefs as a regional impact tipping element (high confidence)", there is no reason why the HTS should not be considered. In fact, the list of climate or Earth system tipping elements is growing in recent studies and additional tipping elements are continuously been proposed driven by deeper understanding of new complex systems. Thus, we think it is valuable to use the HTS as an example tipping element in the biosphere here, even if the literature on it is sparse and we are uncertain to what degree it shows tipping behaviour. Importantly, also, we stress the speculative nature of this tipping element in the section, but nonetheless consider it an illustrative example of the impact of SRM on systems like these, as well as highlighting the advantages of the more qualitative method we have used to come up with first order indications (ie that it is feasible to establish some evidence-backed hypothesise in the absence of modelling data).

We have now rewritten the section to first make the case that the entire system from the Himalayan glaciers to the wide subtropical and tropical plains to the Bay of Bengal is a single integrated system and a unitary Earth System tipping element, albeit one that is underrecognized and understudied as such (we haven't found previous literature that argues for this specific point, and therefore argue for it in this section). It is integrated by connections made by water: the river networks that emanate in the Himalaya and terminate in deltas that richly sustain biodiversity. These river networks support much of the life on the subcontinent, together with the integral and integrating effects of the monsoon, that controls and nourishes human and natural systems. We realize that emphasizing separate elements of this system in the previous version did not clarify this, and we have modified the text accordingly. Like the many different forests and ecological regions of the Amazon Basin, which reaches from the foothills of the Andes to the Atlantic and encompass river networks and rainfall regimes that determine ecological drivers and feedbacks to climate, the Himalayan-to-Sundarbans system is a huge, diverse system that interacts with natural systems, human systems, and climates, and is properly regarded as an important Earth System tipping element as explained above. In contrast to the Amazon, it is barely studied as such. The Indian subcontinent is a region with growing bodies of SRM research, and as such, bringing attention to a hardly studied, potential tipping element and the impact of SRM was considered by us to be valuable enough to include in the paper.

Comments to Table 1, which is really helpful:

We have significantly edits table 1. It now has 4 columns. The 1st column contains the name of the tipping element. The second has the 'effect of SRM on drivers' where we decompose the impact of SRM on each of the drivers, and contain our overall judgement (and a representation of our uncertainty) of the impact of SRM on the drivers overall (ie how useful may SRM be in preventing tipping). The third column contains a description of SRM's ability to reverse tipping once tipping has started but before the system is in a

stable alternative state. Finally, we have a column commenting on the strength of the evidence base.

1. Column: Overall confidence of what is meant here? Overall confidence of SRM being able to reverse tipping? Overall confidence (=agreement) of the literature on column “Can SAI reverse tipping”

We have modified the table significantly. We no longer have an overall confidence column, instead we have a) a representation of our uncertainty in our overall judgement with regards to the effect of SRM on being able to prevent tipping (in the drivers column) and on the strength of the evidence base. This means the ‘overall confidence’ is decomposed further, and clarified with regards to the different things it means.

2. Rows “Dipterocarp Forest” and “Indian Subcontinent Biodiversity Hotspots”: How can SRM help once tipping is completed (as noted in “b. Likely” in column 4). Once biodiversity is lost or a forest has died back, SRM cannot help to restore these systems as they have developed and adapted over millions of years.

Unfortunately this is true, and seems to have been an unintentional error on our parts, so we thank the reviewer for noticing this in such a crucial part of the paper. We have removed Dipterocarp from the table. As reversibility has been clarified to refer to reversal once tipping has started but before it is completed, it is possible for SRM to reverse it. However, the evidence base on reversibility for the HTS is very sparse (partially due to little modelling of tipping behaviour so far, and due to the complexity of ecological systems), and so we no longer state it is ‘likely’ that reversibility could occur, but rather that it is unlikely with high uncertainty.

Section 6.1 (Further Research): I suggest to keep these sections short because for each of the tipping elements, it is already discussed where future research can broaden knowledge.

There is a number of smaller points - Minor points:

Abstract: Please write SAI in the abstract out at first occurrence
This has been done
Page 2, line 45: Also cite Levermann et al., 2012: https://doi.org/10.1007/s10584-011-0126-5
This has been done.

On page 846 is a definition of tipping elements
Page 2, line 53-56: The definition of ecological tipping elements is unclear. In Armstrong McKay, tipping of ecosystems means a large-scale state shift of the Amazon rainforest, boreal forests, or coral reefs. The death of single species does not constitute a tipping in the Earth system sense. Please clarify.

We agree with the reviewer here that according to the McKay22 definition, extinction wouldn’t constitute tipping. However, it is important to clarify that

McKay22 discusses climate tipping points, and whilst we focus on climate tipping points, we do include broader earth system tipping points as well. Agreement on definitions is an inherent difficulty in interdisciplinary collaborative efforts, however, in the ecological and evolutionary literature, rapid population loss can constitute a tipping point (eg https://doi.org/10.1111/evo.13374). Whilst it is true that the scale is not that of an earth system tipping element (and we have clarified that we do only focus on the system level), we have kept a brief mention of this to highlight the difference in language use in the fields. We understand how the inclusion and current phrasing could cause confusion, and we hope that our clarification that "the ecological literature refers to tipping points not only with respect to such changes at the system level (which we focus on here), but also in to the point at which the extinction of an individual species becomes inevitable (e.g. Osmond and Klausmeier 2017)."

Page 2, l 59: Can you directly here give an example of a threshold-free feedback? (maybe this is a good spot for figure 3)
We agree with the reviewer, and have added figure 3 here, as well as the example of methane hydrates
Page 3, l 79: "… has been exceeded for sufficiently long times" What you mean are so-called *overshoots*. Replace citations by

1. Ritchie et al., 2021: https://doi.org/10.1038/s41586-021-03263-2
2. Wunderling et al., 2023: https://doi.org/10.1038/s41558-022-01545-9

This has been done

Page 4, l 99: Irvine et al., 2019 does not exist in the reference list but only Irvine et al., 2018. Please check.
This edit had been carried out
Page 7, l 184, cite Levermann, Winkelmann, 2016, The Cryosphere: https://doi.org/10.5194/tc-10-1799-2016
This edit has been carried out
Page 13, l 369: Did the authors really mean 2089, not 2099?
Yes, the study cited goes up to 2089
Page 26/27: Formatting changes twice, please check.
This has been sorted
Page 31, l 894: The Schneider et al., 2019 paper on a 10°C warming due to cloud changes is speculative (given its huge temperature feedback). This should be stated somewhere around these lines.
At the first mention of this temperature projection, in the previous sub-section, we now note that this was a highly idealized study. For this second mention we have edited the text to remove the specific reference to the magnitude of the warming.
Page 37, chapter 5.3. Amazon basin: In the introductory paragraph, the combined adverse influence of deforestation, human-made fires, and climate change on the Amazon rainforest could be discussed more directly.

Somewhere in this section, the new Bochow et al., 2023, Science Advances paper should be cited: 1126/sciadv.add9973

We have added text that includes a citation for Bochow et al (2023)

I believe MCB (probably Marine Cloud Brightening) is only used as an abbreviation

This has now been edited

Page 46: I think this study by Rao et al., 2023 in Communications Earth and Environment should be discussed briefly in this section (https://doi.org/10.1038/s43247-023-00910-6)

This has now been added, and we are thankful for the reviewer for making us aware of this paper.