Responses to Reviewers

Reviewer 1 Comments

The authors have carefully carried out the recommendations by the reviewers and fully covered my concerns. In particular, the presentation improved much (Figures, Table). Still, if the authors see potential to streamline the text, I would appreciate these efforts as well as even clearer figures. In particular, Fig. 3 would profit from less abbreviations, number of question marks, etc.. This is similarly valid for Table 1. Apart from these technical corrections (that I leave to the authors to work over or not), I am very happy to recommend this paper for publication in ESD. And I am happy to congratulate the authors to this very large and important review paper.

We thank the reviewer for their very kind comments, and generally wish to thank the reviewers previous set of comments in helping to substantially shape the paper.

Unfortunately, we have not been able to streamline the text, particularly given the need to address reviewer 2 comments about the HTS.

To make Fig. 3 clearer, we have added the meanings of the abbreviations in the text description. We have reduced the abbreviations used in Table 1, using full words for the overall judgements, and clearer abbreviations (Worse for Worsening, No for No compensation, Part for Partial Compensation, Eff for Effective Compensation, Over for Overcompensation and Unk for Unknown).

Armstrong-McKay Comments

General comments:

The authors have substantially revised this manuscript, tightening the writing & structure and reducing repetition throughout, and in my view, it has improved considerably as a result. In particular, the authors have caveated their summary of overall SRM effectiveness for CTPs more thoroughly, emphasising the uncertainties brought by non-temperature drivers in the abstract, introduction, and discussion (while the counter-point made that this could also make SRM more effective, not only less, is fair enough too). The additional figures and tables are useful, better helping to demonstrate tipping dynamics, how SRM might intervene in these dynamics, and the paper's results. Table 1 has also improved with the addition of more explicit discussion of drivers, effectiveness, and confidence throughout, making it easier to discern key points. Other points raised, for example the ocean temperature focus for marine ice sheets, or current

general circulation / Earth system model limitations, have also been clarified, and the authors have justified their selection of systems to consider in this paper.

We thank the reviewer for his kind words and helpful feedback in both this, and the previous, round of reviews.

Beyond minor further suggestions, my main remaining comments concern the subtleties of categorising tipping in the Himalaya-to-Sundarbans (HTS) hydro-ecological system. While I appreciate the value of looking at HTS as an integrated socio-ecological system likely featuring localised tipping points, I am not yet convinced that it can be categorised as a regional/impact tipping element by the rationale of AM22 (even as a highly uncertain one) without a clear mechanism for shared tipping dynamics at the system rather than subsystem level beyond a common threshold. For comparison, warm-water coral reefs are classed as regional elements because there's evidence for a bleaching frequency threshold beyond which recovery is prevented and localised die-off becomes inevitable, with widespread mortality across the same biome/ecosystem functional group occurring at similar warming levels. Similarly, while Amazon rainforest dieback due to moisture recycling failure is also localised, it can trigger further dieback across much wider parts of the same system via that process, and is all one biome/functional group. In contrast, HTS covers multiple biomes/ecosystem functional groups, with the default likelihood being that different habitats that may tip are likely to tip due to different dynamics at different levels of climate change/degradation. It's still fine to include HTS in the paper though, but I think it either needs a little more justification as to how systemic tipping might emerge at the integrated system level, or a little more clarification that it's socio-ecological system with localised tipping, which this paper is suggesting as a potential element but is still a valuable case-study for considering SRM impacts on even if not.

We believed we have addressed many of the reviewers issues with the HTS section, with the comments related to this by the appropriate Specific Comment. The HTS section as a whole has been substantially revised to focus on what may make it a single integrated tipping element, whilst there is now also greater acknowledgement of the uncertainty of this hypothesis

Specific comments (by line no.):

23: I think “could” or “is likely” rather than just “is” is more appropriate here, given most of the evidence comes from simulations.

This has been done, and changed to ‘could be’. Line 23.

38: A comma has escaped.

This has been deleted.

47: Should “reverse” be here as well (along with avoid/postpone)?

This has been added, line 48-49

61: “stop increasing” would be smoother than “stop to increase”.

We agree, this has been changed, line 62.

130: “tipping elements” would be more consistent terminology than “earth systems” here, or Earth subsystems to differentiate from the Earth system as a whole.

This has been changed to “earth sub-systems (tipping elements)”, line 131

144: Insufficient SRM possible/used is also highly relevant for only postponing tipping.

We have mentioned this now, although only discuss it here as it is different to the peak shaving scenario we use. We say the following on line 145-148:

“Moreover, if insufficient amounts of SRM were used - maintaining, for example, a constant SRM forcing rather than the constant Global Mean Surface Temperature (GMST) assumed in the peak shaving scenario - SRM may also only postpone tipping.”

175 / Table 1: The table is much improved, but I had to repeatedly look back at caption to remind myself of what each letter meant in the second column. A simpler approach to consider might be pluses and minuses, e.g. - for worsen, ~ for negligible, + for partial compensation, ++ for effective compensation, and +++ for overcompensation (however, that’d mean +/-s for both driver and compensation direction, so that might be too confusing...), or just abbreviations e.g. over, part, etc. Also, I assume bolding for drivers means primary drivers, but I don’t think this is stated (and is missing e.g. for MSC driver or HTS driver/reversibility). I was going to ask too whether it’d might make more sense to have Table 1 plus its description (lines 194-205) after Section 5 instead, but on reflection I can see it can be argued either way which makes more sense to the reader. Finally, I broadly agree with the categorisations, though I’d query a few of the overall ones, such as whether HTS should be U-P (as the uncertain effect of SAI on monsoons could be critical), whether AR should be U-P or W-P (as evidence / GCMs remain limited, and while I agree it works better in east than west, there remains an uncertain

risk of bringing west to point of bistability instead), whether SPG should be U-E (as no driver has an N or W, but there are few studies), and whether BPF should be P-E (as studies find reduced permafrost loss, but not totally countered, albeit potentially improvable via SAI strategy).

We have changed to shortened versions of the words (Worse (for Worsen), No (for No Compensation), Part (for Partial Compensation), Eff (for Effective Compensation), Over (for Overcompensation) and Unk (for Unknown). We also include the full words for the overall judgement of each tipping element.

We have included the initialisms in the figure caption to aid readability.

Bolded does mean primary drivers and we have added these.

We have amended the HTS system to Unknown, because of the possibly decisive influence of the monsoon.

For the Amazon Rainforest, we have clarified that in the West it is W-P, but do believe that the Eastern Amazon tipping would be more significant if the entire tipping point were to tip, so feel confident that we could say, with the clarification we have in place, that the Amazon is No compensation-Partial compensation.

For the SPG, whilst there are few studies, hence the maximum uncertainty, the studies that do exist don't suggest that it is likely to Worsen it however.

For the BPF, the reason we are comfortable saying it is Effective is that the Effective range is 75%-125% compensation. Both studies that allow percentages to be calculated (Chen et al., 2023; Liu, Moore and Chen, 2023) exceed our 75% threshold.

Fig. 3: I believe the compensations here are the overall compensation judgments in Table 1 (rather than temperature alone), but would be useful to state in the legend or caption for clarity.

This has been clarified, we have added "*The compensation and uncertainty judgements is our assessment for the overall effect on drivers from Table 1.*"

222-244 & 286-287: This is indeed the IPCC AR6 summary, but the nature of confidence language makes it sound less compelling than I think the evidence suggests (especially from palaeo studies) - AR6 for example reported several studies where total loss committed at 2-3°C (ch.9-pg.78). As such, so that it doesn't sound like tipping is unlikely (rather than uncertain) below 3C, if space allows I'd suggest clarifying that this

is specifically the IPCC AR6 assessment and briefly mentioning that some studies do find evidence for past collapse within this range.

We have edited this, adding in sentences in both paragraphs. We clarify that the uncertainty judgements are from the IPCC AR6 report, cite paleo evidence, and highlight that Lenton et al. 2023 puts the critical threshold at lower than the IPCC for both.

323: Double citation.

This has been removed.

385: Pedantic, but “like the Greenland Ice Sheet” to be specific to the icy bit of Greenland.

This has been changed

402-403: Should clarify the temperature level in G3 for unfamiliar, i.e. 2020 levels I believe. Also, maybe better to have this sentence integrated in to paragraph above rather than free-floating?

We have clarified that G3 is projected 2020 levels and the paragraph has been integrated.

574-575: Some caveats on phrasing here, as while we do refer to this as a "global/core tipping element", referring to a "global tipping point" in a permafrost context can be misread, as it is often associated with the idea of a runaway warming threshold in the permafrost carbon feedback at the global scale (which the recent assessment by Nitzbon et al. this year [https://www.nature.com/articles/s41558-024-02011-4] is clear in ruling out). Nitzbon et al. also assess the Yedoma scenario as unlikely (although they do support localised abrupt thaw as tipping, albeit without a specific threshold warming level), which is worth mentioning here for context. Lastly, more accurate to say “becomes more widespread at” rather than “could occur at”, given some abrupt thaw is already happening (our threshold estimate here is for when localised tipping becomes regionally/globally widespread in a near-synchronous manner, as for coral reefs).

We have edited the text, including adding “Others, however, have suggested that no such global mean temperature threshold applies, with global permafrost loss being quasi-linear in global warming throughout its decline (Nitzbon et al., 2024). If asuch a global temperature threshold at 4°C exists”

598-599: Do you mean less effectively than limiting GMT through zero emissions?

No, we meant that the fractional restoration of permafrost is modeled to be smaller than that of GMT. The same logic as with the % compensations in table 1. I.e. when cooling from 2 to 1C, the permafrost might change from that of a 2C GHG-warming world to a 1.2C GHG-warming world. We have edited the text to make this clear, saying "However, global SRM strategies typically under-restore permafrost relative to their impact on global mean temperature"

655-669 / Fig. 4: (6) is not explicitly labelled in caption (e.g. before "It sinks along the shelf edge").

This has been added there

680: I think until after 2100 would be more accurate

We have edited it, as these scenarios also don't expect post 2100 collapse. Rather, it now reads "in general models do not predict collapse for SSP scenarios extending to until 2100 (Weijer 2020), although some models show collapse for extreme hosing (Jackson 2023, van Westen 2023) or warming (Hu et al., 2013). "

709: Anthropogenic global warming, for clarity (as can't rule out palaeo warming events triggering circulation collapse).

This has been changed

722: Not a major issue, but is this the first time this compensation language is used in main text outside of table 1? It's useful, but feels like could be more consistent throughout if used.

Whilst we somewhat agree, time constraints in this review iteration has precluded us from doing so

885: GHGs are defined in Intro, so no need to redefine here.

Edited.

1161: Relevant here is this recent paper, also in this SI:
https://esd.copernicus.org/articles/15/671/2024/esd-15-671-2024.html

We have added in discussion of this paper. In particular, we have said

"The response of coral calcification to acidification is generally linear and highly species specific, so a simple 'coral acidification tipping point' does not exist. Other factors, such as internal pH regulation, may have physiological tipping, points, but manifest as linear decreases at

an ecosystem-wide level. However, coral reefs are complex communities with non-coral species playing important roles, and whilst most acidification impacts are linear, there does seem to be some evidence of tipping on a local scale due to the indirect effects of acidification on the overall health of the community in specific habitats, particularly those with an already high pCO_2 (Cornwall et al. 2024). Nonetheless, these are unlikely to manifest as a global, near-synchronous, tipping point."

1196: Phytoplankton are indeed under-studied on this, but corals & symbiont algae are relevant here (statement is equivalent for all though).

We agree and have changed phytoplankton to "zooxanthanae algae"

1232-1234: I think this should be caveated more upfront here, making it clearer that you are advocating this system as being a plausible candidate for a tipping element for the first time here,

Acknowledged as suggested

with this section making the case for it being a tipping element as well as SRM's likely impact on it. Otherwise, as phrased it to me it can be read as saying it's already been established as plausible, which I don't think is the case yet.

Thank you for this suggestion, we changed the text as recommended here.

You should also rephrase the part in parentheses, as to me it implies that we suggest HTS as a candidate regional/impact element in AM22, rather than the category of regional/impact element being proposed in AM22.

Changed as suggested in this section

1239-1242: I think this is a good framing and caveat, as much like some threshold-free systems are considered in this paper the HTS doesn't need to be a tipping element per se to be considered, and there is value in considering SRM's affect on tipping cascades in socio-ecological systems. As it stands though, I personally don't think sufficient evidence is presented for tipping to be likely at the integrated system level, but that doesn't mean it shouldn't be discussed.

We have substantially edited the section to acknowledge that what we are essentially presenting is a hypothesis of integrated, systemic tipping, and acknowledge it is based on limited evidence. We also agree that this is not necessary for inclusion in the paper, and acknowledge the (significant) possibility that this may not in fact be a single, integrated tipping element, but a collection of interdependent ecological tipping

elements that may not show systemic tipping. Nonetheless, we do also think that we have included a stronger case for integration here.

1246-1251: The key difference between heterogeneity in HTS vs Amazon/corals is that shallow tropical coral reefs and the Amazon rainforest (NB, we consider the Amazon rainforest to be the tipping element, not the whole Amazon basin, as it shares a common tipping dynamic within same biome) are all the same biome/ecosystem functional group, whereas HTS integrates quite different biomes.

Deleted 'basin' ; while the rainforest is considered a biome, there are many different forest types within this biome in the Amazon and across other areas. However, it is clearly true that the HTS consists of many biome types. Not to argue this point too far, the concept of 'biomes' is poorly defined and descriptive, and every map of the world's biomes defines them differently, so one doesn't want to rest a definition of tipping elements too much on this as a foundation. Ecologists treat the concept of tipping somewhat differently than do climate scientists, although no less seriously and urgently, and similarly as total system changes, so there's that as an issue here as well.

Furthermore, the evidence presented for alternative states emerging are to me all evidence of ecosystem state change under continued pressure, but insufficient for full regime shifts to a new and self-sustaining alternative state. A degraded ecosystem can be quasi-stable under sustained pressure, but to prove it's in an alternative state / system attractor in a dynamical systems sense (the theoretical underpinning to tipping points), one would have to demonstrate that feedbacks exist that would maintain this new state even if the pressure relented, instead of allowing recovery to an original-like state (albeit with some adaptive differences between original and recovered state, as per Holling's ecological rather than engineering resilience). Invasive species are a candidate driver in this sense (e.g. cited in GTPR23 as playing a role in localised tipping in savannah/dryland ecosystems), though whether it could act as a driver at the integrated system level for the HTS rather than some specific habitats within it is harder to see.

We have revised the text to make a stronger case for possible tipping of this entire system. The comparisons between tipping to alternative states in the ecological literature are very interesting points here, but would be too tangential to discuss at length in this paper. A sentence was added mentioning this. It is well established in the ecological literature that many novel ecosystem states are irreversible, and species extinctions, particularly for dominant or keystone species, that certainly is irreversible. Because large numbers of species extinctions are central to the changes discussed here, it is a solid assumption that the system itself is likely to be tipped irreversibly; invasive species, soil erosion, and other changes add additional nails to the coffin.

1259-1261: Good to be thinking about the alternative state would be (bearing in mind need for additional dynamical evidence mentioned above) – would low diversity grasslands be expected across all topography though, given the spatial and climatic heterogeneity?

This is merely speculative on our part, based on some observed changes in this and other systems. But it is uncertain.

1264-1266: For HTS to be considered one integrated tipping element (in line with AM22/GTPR definitions, at least), I think the tipping dynamic for it either needs to be a process spanning and involving all of these sub-systems, or be the same tipping dynamic in each of them but with near-synchronous thresholds. As it stands it feels more like tipping is possible within each HTS ecological, agricultural, and human sub-system without a clear common tipping dynamic or threshold across them all, with correlation in their degradation/tipping more likely to be due to sharing common drivers in warming and habitat loss/degradation rather than direct causation between them.

We are speculating that there is a real possibility that what links them are the two sources of water on which all of the ecological and human systems depend: the river systems originating in the Himalayan glaciers, and the monsoon. Warming and land-use change, including river damming, exacerbate and interact with these central, fundamental drivers, the sources (and timing) of water. While climate and SRM might drive complex changes in water from these two sources (e.g. snow vs. rain in the Himalaya, flooding vs. drought (both are not only likely, but happening already), changes in the seasonality of water availability relative to temperature seasonality, rising sea levels and coastal erosion), these effects on water are felt across a very large scale and across diverse systems. It is unclear and perhaps unlikely that there is a single, unique threshold (that is, a point that is reached for a certain number of mm of water on a certain day) for all of the HTS, but that is really also the case for more familiar systems such as coral reefs and Amazon forests. For example, habitat fragmentation due to development and road construction in the Amazon rainforest, combined with drought and high temperatures and human activity, makes fires more frequent, intense and extensive, and these combine to change forest permanently to degraded grassland/shrubland; but this happens in a mosaic patchwork, not to the entire region in a single swipe. One of the authors in particular (JG) also believes that readers need to be prodded to think more broadly at this difficult interface between climate and ecological science, and to consider other less-familiar systems like the HTS, but of course it should be introduced in a rigorous manner.

This is to some extent true of coral tipping too, as tipping dynamics are localised to each reef rather than spanning the whole element, but the reason we grouped those as a tipping element anyway is that they share a common specific tipping dynamic (i.e.

bleaching recurrence leading to mass mortality) with likely regionally-to-globally similar warming thresholds (i.e. ~1.5C) leading to near-synchronous tipping across the whole biome/functional group. Ideally then there'd be some discussion of whether there's a specific process that could feasibly span across the whole HTS system and precipitate tipping in its subsystems at approximately the same level of climate change, or highlight this as a gap to explore in future before HTS can be considered as a regional tipping element.

We are positing that the driver is a single connected hydrological system of water availability across the entire HTS region, originating from the Himalayan glaciers feeding a network of major river systems that cross the subcontinent and end in the Indian Ocean, plus the regional monsoon. It is at present difficult to identify a clear threshold, but it seems plausible that the entire system would be affected by these changes in a linked manner. There are certainly great gaps in our awareness and understanding of these linked, potentially integrated changes!

1276-1278: As above, are these drivers for tipping in each HTS sub-system, or for integrated HTS system as a whole?

We are arguing that these hydrological drivers are linked for the HTS system as a whole.

1294: Are the Western Ghats part of HTS as defined? The west coast of India seems a bit far removed from Himalaya-to-Sundarbans. (Eastern Ghats would make more sense, but even they don't quite make it to edge of GBM drainage basin).

You are absolutely correct! That was incorrect and has been deleted.

1321: Suggest changing "Earth System" to "climate", as the Earth system view is that climate, biological, and human dimensions are all aspects of the overall Earth system they are all a part of.

Changed to "climate" as recommended.

1351: AM22 not necessarily the best citation on this – we compiled more evidence & papers on boreal tipping dynamics in the GTPR23 biosphere chapter: https://global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/

Citations more directly relevant have been used now.

1359, 1363 & Table 1: Permafrost "melting" should be permafrost thawing for accuracy.

Changed to "thawing" or "thaw" throughout.

1394: Cite Table 1 here as discussing results it summarises (could arguably have table here rather than up top too, but I can see arguments for placement at either place).

We have cited it.

1398-1399: Sentence a bit fragmented here, and probably need to clarify for readers why AMOC can overcompensate in previous sentence but not compensating here.

We have edited this section for clarity, saying " For two tipping elements, the effect of SRM at a minimum did not compensate for the overall effect of climate change on their drivers. For one of these two tipping elements, AMOC, we determine the range of feasible impacts of SRM to extend from not compensating for, to overcompensating the impacts of climate change on its drivers - this is the only tipping element where SRM was seen to feasibly overcompensate the overall effect of climate change on its drivers."

1400: And for some elements, we're not fully sure of the relative importance of different drivers yet either.

We have added in a sentence stressing this "Furthermore, our 'overall judgements' were based on our assessment of the relative importance of different drivers, and for many tipping elements this is not fully known."

1448: I like this uncertainty typology, makes discussion very clear.

Thank you

Table 1 & Supp. Info.: SPG is misspelled as SGP in several places (e.g. SI line 18, 74; Table1 SPG row evidence strength column), so need to check through for that.

We have changed this

Author Roles in reviewer comments: GF responded to all reviewer comments except for those concerning the biosphere section which were responded to by YF and JG