ESD Ideas: Climate tipping is not instantaneous – the duration of an overshoot matters
Reviewer Responses

We are grateful for the constructive reviewer comments received on our manuscript. These comments are repeated in black, and our responses are given in blue.

Response to Reviewer 1

Ritchie et al. use a conceptual/mathematical framework to quantify which tipping elements would tip when overshooting 1.5^{o}C global warming on different timescales. The article is concise and well-written, and the methods are clear and well-established. The topic of climate overshoots is obviously very relevant and well-suited for ESD. However, I have some concerns regarding the framing of the results, especially given the expected broad readership, and the lack of an assessment of uncertainties, which should however be straightforward to implement.

General/major comments

1. Novelty: This may of course be due to the length constraints, but the idea does not strike me as particularly "innovative" per the description of the "ESD Ideas" format. For example, overshoots of the Paris Agreement have previously been explored in a more comprehensive setup (including idealized interactions between different tipping elements) by Wunderling et al. (2023), which is not cited. In my view, this does not preclude publication of the present manuscript, but the authors should motivate the need for this piece more explicitly and position it better within the existing literature. One option would be to target a broader/policy-oriented audience. In this case, the following point would be especially relevant.

Yes, we intend to target a broader and policy-oriented audience to highlight the importance that tipping is not committed upon crossing the threshold. The novelty of the Idea is that for the first time it provides an assessment for the implications of overshoot for all tipping elements (as opposed to a select few as previously considered) identified in the Armstrong-McKay et al. (2022) study. Interactions are not included in this study and that is now mentioned in the manuscript citing the more recent review by Wunderling et al. (2024), however, the thresholds are at least partly informed by climate model simulations which have some interactions built in.

2. Policy message: Since this is a short article which I expect to be accessible to a rather wide audience, it would be important to both consider and explicitly acknowledge its policy implications and applicability.

Most importantly, the article should be very clear upfront that some (many?) of the underlying overshoot trajectories are neither physically nor socio-economically plausible. For example, a 4–5^{o}C overshoot before a 1.5^{o}C global warming stabilization within 100 years seems clearly unfeasible, but the avoidance of tipping under such unrealistic scenarios could a give a false sense of security that strong warming in the medium term would not be as dangerous. The recent paper by Schleussner et al. (2024) is worth a read (and maybe a cite) in this regard. They conclude: "[T]echnical, economic and sustainability considerations may limit the realization of carbon dioxide removal deployment at such scales [of several hundred gigatonnes]. Therefore, we cannot be confident that temperature decline after overshoot is achievable within the timescales expected today."

To prevent any misinterpretation by readers or decision-makers, I think it is essential that this article cautions which of the results might be applicable to current global warming and which are not.

The policy message of the manuscript has been enhanced by providing a new opening paragraph to put the study into context. We also agree with the reviewer that some scenarios are unrealistic (without large scale geoengineering intervention) and so we now write "It is important to highlight that not all of these overshoot profiles would be plausible, even with carbon dioxide removal technologies, particularly the front right corner. Specifically, considerations such as technical, economic and sustainability can limit the scales required at which carbon dioxide must be removed for such overshoots to be possible (Schleussner et al., 2024). Moving away from this front right corner and towards the back left corner coincides with increasing the feasibility of the overshoot profiles." Note that identifying the precise boundary for when overshoot scenarios become unfeasible requires further research.

3. Minimal assessment of uncertainties: Overshoot timescales of the order of a human lifespan (Fig. 1b) are probably most interesting and relevant for a broad readership. However, assessing overshoots on these timescales in a non-probabilistic way could give a distorted view of the associated risks. In addition, the article is currently not clear about this omission: for example, "three are likely to tip" in L41-42 suggests that some probabilistic assessment might have taken place.

Since Armstrong McKay et al. (2022) provide confidence intervals for all GW level estimates and for most timescale estimates, it should be straightforward to turn the deterministic Fig. 1b into a probabilistic one, which could show a probability distribution (e.g., as a violin plot) of the number of tipped elements for each global warming level when taking into account parameter uncertainty. This would mean that it could not be shown which elements would tip in each case, but I would deem that an acceptable trade-off since the current Fig. 1b is already a part of Fig. 1c. I think it is ok to keep Fig. 1c as it is, but to remind the reader in the text that uncertainties are neglected here.

In Fig 1a and 1b we now provide an assessment of uncertainties, and have kept Fig 1c the same as suggested. Instead of violin plots, we have used colour to represent the probability density in an effort to keep the figure as simple as possible. Detailing the methods, we now write at the end of the Supplementary Material "Panels (a) and (b) in Figure 1 of the main paper, plot the probability density for the number of tipped elements in colour. An exponentially modified Gaussian distribution is fitted, using least squares, to each element's tipping timescale and threshold location. The lower, best, and upper estimates are assumed to correspond to the 5, 50, and 95% cumulative probability density levels. In the scenario where no estimate is given for either the upper or lower value, the best estimate is used instead. A random sample is then drawn from each of the 32 distributions to provide the threshold location and tipping timescale for each of the 16 tipping elements. Assuming these threshold and timescale values the inverse square law is used as previously to calculate the number of elements that would tip for each warming scenario. The process is repeated 1,000 times to thus generate the probability density for the number of tipped elements for each scenario."

The results remain qualitatively the same; importantly, there is still a large reduction in the number of elements that would undergo tipping if the overshoot duration is restricted to 100 years (Fig 1b) compared with stabilising the temperature at its peak (Fig 1a). The main text and figure caption has been re-worked to reflect these changes.

Specific and minor comments

L2–3: "as is often assumed": please provide one or two references that this is indeed the case – maybe from the scientific literature, or from media or the policy sphere. This is an important point because the entire article addresses an alleged common misconception that tipping would be instantaneous, but it is not shown that this misconception actually exists.

We have now added a reference in the main text where a similar statement appears as opposed to in the abstract. We have made a slight reformulation to mention that a commitment to tipping is often assumed once a threshold has been crossed. Some other examples that make this assumption include "A tipping point is when a temperature threshold is passed, leading to unstoppable change in a climate system..." (World on brink of five 'disastrous' climate tipping points, Guardian Sept 2022); "Crossing Earth system tipping points would have "catastrophic" impacts on societies" (Q&A: Climate tipping points have put Earth on 'disastrous trajectory', Carbon Brief Dec 2023); "Crossing these thresholds would disrupt the Earth's systems triggering the collapse of ice sheets" (Climate change: Six tipping points 'likely' to be crossed, BBC News Sept 2022). Note in the literature and media, a tipping point is often referred to as the threshold.

L16: The number calculated by the Climate Action Tracker refers to 2100 and the websites explicitly states "Temperatures continue to rise after 2100" (https://climateactiontracker.org/publications/the-climate-crisis-worsens-the-warming-outlook-stagnates/). Since you are discussing stabilization values in this paragraph, could you contextualize this?

This is a good point and we now use this to motivate why we also consider stabilising at 4^oC warming, by writing "Current climate commitments have been estimated to lead to global warming reaching 2.7 ± 0.2^oC by the end of the century (Climate Action Tracker, 2024). Stabilising at this level of warming would increase the range to between seven and ten elements tipping, but under these commitments, warming would continue beyond 2100 and so if temperature was to only stabilise near 4^oC, then the range is between ten and thirteen ..."

Fig. 1: Some tipping elements are hard to distinguish just by color, maybe use colors in combination with different hatching patterns?

We have followed your suggestion and in addition use four different hatching patterns to distinguish more clearly between the different tipping elements.

Fig. 1c: I am unsure if the current choice of the logarithmic axis is ideal. An overshoot of 10^5 years may at most be relevant for paleoclimate if we frame interglacials as "overshoots" to a glacial background climate, but probably not for the current anthropogenic global warming. This does not mean that the figure needs to be extensively modified, but the large range of overshoot durations should be pointed out (and put in context) explicitly in the text and/or caption. And maybe consider cutting off the axis at (some) 1000 years?

The "back wall" of Fig. 1c is designed to effectively consider the scenario of no overshoot (i.e. it corresponds to the cross section of panel (a) without uncertainties). We explicitly make reference to this by writing in the main text "Without the uncertainties panels (a) and (b) would be cross sections of panel (c), namely the left-hand "back wall" and the second visible row from the right-hand front, respectively." Furthermore, we want to highlight that the slow tipping elements only undergo tipping for very long overshoots and even cutting the axis at 10^4 years the Greenland ice sheet would not be visible under any scenario.

L26 and following: Are the values in Armstrong McKay et al. really derived from an equilibrated climate (as suggested by Fig. 1a) or from transient simulations? If they are derived from transient runs, wouldn't this lead to a systematic bias when they are used in an equilibrium view?

This is a good point. It is not clear in the Armstrong-McKay et al. (2022) study if the thresholds are derived from an equilibrated climate or transient simulations. However, some of the systems with very long timescales (i.e. major ice sheets) have low thresholds, which would indicate that they are derived from an equilibrated climate. Nevertheless, we do now write in the main text "Furthermore, the threshold values may have been determined from transient climate simulations rather than corresponding to equilibrium values as assumed here, which would bias the results." to acknowledge this needs to be considered as a possibility.

L29: It would be more reader-friendly to include the Supplement directly within the article (e.g., as an Appendix), if this is allowed by the Editors.

We understand this is not possible for ESD Ideas, but can if allowed.

L30 and Suppl. L38: It is not entirely clear how the choice $\alpha = 1$ for all TEs is motivated. Could you check the validity of this assumption, for example, in one or two commonly used conceptual models of some tipping elements (e.g., Stommel model for the AMOC)?

The choice of $\alpha = 1$ is arbitrary and we suggest that this should be an area of future research as the information is not currently available in the Armstrong-McKay et al. (2022) study. Note in the previous version a small mistake was found that meant the α would not affect the overshoot duration (as the scaling on the forcing cancelled out the change of curvature). We have therefore reworked the model slightly, including introducing two parameters. A scaling parameter, β, that does not feature in the inverse square law and the α that still provides a measure of the curvature of the equilibrium curve. We still set $\alpha = 1$ and so the results are unchanged. We have also checked how the allowed overshoot duration compares with that which can be calculated via the Stommel-Cessi AMOC model (Cessi, 1994). If the best estimates of the Armstrong-McKay et al. (2022) study are used then our choice of $\alpha = 1$ corresponds to an order of magnitude stricter condition on the square of the overshoot duration than the Stommel-Cessi model would suggest (a tipping timescale of 100 years would make it the same order of magnitude, but still more restrictive). In the Supplementary we now write "Note that this choice of α corresponds to a conservative choice for the AMOC according to the Stommel-Cessi model (Cessi, 1994), which would allow the square of the overshoot duration to be an order of magnitude larger. However, further research is required to determine the curvature parameter for all tipping elements."

Recently, some overshoot studies have been performed with state-of-the-art numerical models, notably Bochow et al. (2023) for the Greenland ice sheet (see their Fig. 3 for different overshoot durations). It would be very valuable to benchmark (e.g., in the Supplement) your estimates from Fig. 1c against their results to see if the results hold when compared to a comprehensive model.

The results in Fig 1c compare well with the Bochow et al. (2023) study. There it is shown that the Greenland ice sheet does not tip until peak summer temperatures above present day exceed 4 and 5^oC in PISM and YELMO respectively for a 10,000 year convergence time. We think this is an important validation of the theory and so we now write in the main text "Specifically, the Greenland ice sheet does not tip until the overshoot duration is greater than 10,000 years, which agrees well with simulations from two state-of-the-art numerical models (Bochow et al., 2023)."

"Climate Action Tracker" reference should be updated to the most recent version (and equipped with a URL).

We have updated the Climate Action Tracker reference to 2024 and included a URL.

Suppl. L23: "as expecting" $\rightarrow$ "as expected"

Thank you for spotting this, it has now been corrected.

Bochow, N., Poltronieri, A., Robinson, A., Montoya, M., Rypdal, M., & Boers, N. (2023). Overshooting the critical threshold for the Greenland ice sheet. Nature, 622, 528–536. https://doi.org/10.1038/s41586-023-06503-9

Schleussner, C.-F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., et al. (2024). Overconfidence in climate overshoot. Nature, 634, 366–373. https://doi.org/10.1038/s41586-024-08020-9

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D. I., Ritchie, P. D. L., et al. (2023). Global warming overshoots increase risks of climate tipping cascades in a network model. Nature Climate Change, 13, 75–82. https://doi.org/10.1038/s41558-022-01545-9