**Response to Reviewers for Hessen et al., Lake ecosystem tipping points and climate feedbacks**

*We thank the reviewers for their positive judgment on our ms, and the very constructive comments. We outline below revisions in response to the general and specific points raised by each reviewer. We thank the reviewers for the suggestion to broaden the scope of the paper. We acknowledge that the original submission followed a definition of 'tipping point' applied in the report, 'Global Tipping Points' (Lenton et al., 2023) presented at the recent COP28-meeting (which is now cited); namely that there should be self-reinforcing feedbacks and evidence of hysteresis (as explained also in the ms). We have now explained this rationale in the manuscript along with considerations of broader contexts as recommended by the reviewers. A number of new references have been added to support our conclusions, and also to provide examples as suggested by RC1. The revisions are more than those pasted in the responses below, but the major revisions directly addressing suggestions or requests are refereed to with line number and revised text below.*

**Reviewer 1 (RC1)**

The contribution by Hessen et al summarises candidate tipping points (TP) in lake ecosystems focusing on their role and connection to climate feedbacks. The paper is something between a review/synthesis based (apparently) on the expert knowledge of the well-recognised author's list.

My main difficulty relates to the fact that it is not clear how the selection of the 6 candidate tipping points was made. The authors refer to the literate presenting tipping points but it is not clear what literature review was made, or whether these are already identified tipping points that the authors in this paper revisit according to their definition.

In this respect, it is feels a bit odd that out of the 6 candidate TP 3 are presented as not being TP (salinisation, shift to N-P limitation, invasive species).

Could these three make part of the discussion rather the main text?

*Response: We acknowledge that this could be confusing, and that the rationale for the selection both for the 6 candidate tipping points and the "chosen ones" should be clarified. This is now done in the revision, but in brief the author team, based on their wide experience in freshwater ecosystem research and insight in literature, proposed "candidates". We also searched the literature for hits on tipping points AND lakes (or ponds), and used this as an entry to the selection of relevant categories and cases. We agreed on 6 candidates with potentially widespread and relevant consequences. Among these, 2 could be considered as "real" tipping point categories according to the criteria of self-reinforcing feedbacks and hysteresis (rationale for definition now included in ms), 2 are type "binary shifts, and the last 2 represent potential threshold effects. We think all these cases are interesting by representing potentially widespread and to some extent climate driven non-linear responses, also often with repercussions to climate by GHG-emissions. This is further clarified in the revision.*

Line 59-69: Some types of changes can be classified as *binary*, i.e. either-or situations at the system level. Increased temperature and/or reduced precipitation may induce negative water balance and shrinking of water volumes to the level where lakes or ponds simply disappear. Many lakes worldwide are facing reduced water volumes, but perhaps most striking is the widespread loss of high-latitude waterbodies, from Arctic or sub-Arctic ponds to wetlands or bogs. Such phenomena may qualify as one type of tipping point, but are not self-propelled by internal feedbacks *per se*, but rather by higher evaporation to precipitation ratios (Smol and Douglas 2007) or permafrost thaw (Smith et al. 2005; Webb et al. 2022; Smol 2023). While most tundra-ponds and other small waterbodies hardly qualify as *lakes* in the common sense, we mostly use the word lake through the text for simplicity, yet it will be evident from the context of wording where we specifically refer to ponds.

Now the discussion has an interesting part in connecting the first two TP (eutrophication, increased loading) but for the rest stays a bit generic on the issue of what is a tipping point or not for a lake in terms of persistence in time or abruptness.

*Response: We thank the reviewer for this important observation. This reflects that we arrived at two "real" tipping point categories according to the applied (and strict) criteria, but we feel that the discussion of the nature or type of non-linear responses is also important, since binary changes such as presence or absence of water bodies, salinization above tolerance thresholds for ecosystems (or key species), irreversible changes due to invasive species etc may pose mayor shifts in systems, partly caused by climate changes and partly with climate feedbacks. The text has been revised substantially and notably for the four non-TP categories. The changes are too many to be be pasted below, but will appear from the revised ms per se.*

Also the waterbodies disappearance seems to be more of a tipping cascade rather a TP.

I miss a definition of binary shifts.

Also it is not clear what are tipping categories.

*Response: We agree, the disappearance of waterbodies is not presented as a TP in accordance with the strict definition. However, we do not consider this phenomenon to be 'cascade' per se, in that it is unlikely to be self-propelling. Binary shifts is an 'either-or' situation (presence-absence), and we have clarified this important point in the revised ms. See also the revised text above (L 59-69) as example. Also, in line with suggestions from ref. # 2, we have included negative water balance, and not only permafrost thaw, e.g. L 374-379-541: While the main problem is loss of water bodies affected by warming-induced increased evapotranspiration rates (Smol and Douglas 2007) and permafrost thaw (Smith et al. 2005), there are also cases where collapsing palsas and thermokarst areas create new waterbodies, and these waterbodies may themselves represent a positive feedback by accelerating the thaw (Langer et al. 2016; Turetsky et al., 2020).*

It would help to provide examples of actual lakes with the mentioned tipping points.

*Response: Many thanks. We acknowledge the space limitations but agree some real examples are important. We have now included real-lake examples for all categories, e.g. for eutrophication, L199-210: Warming also increases stratification and the duration and strength of stratification, also promoting anoxia (Maberly et al. 2020; Woolway et al. 2020; 2022). As a case example, this phenomenon is well documented by the recent study of the*

*Danish, shallow and highly eutrophic lake Ormstrup (Davidson et al. 2024). For browning (L 323-325): A well explored case study as an example of these impacts, which is also linked directly to the tipping point concept, is the Swedish, boreal brownwater lake Härsvatten where a long-term study clearly links loadings of DOC to anoxia (Spears et al. 2017). For loss of water-bodies (L380-388): Since most of these potentially lost waterbodies are small and nameless ponds, it is hard to point to specific cases, but the works cited above provide a number of telling examples. While the focus in this context is negative water balance or loss of high-latitude waterbodies, this is actually a widespread problem causing shrinking of many lakes. In Arctic areas, responses to warming may differ substantially between perennial lakes and ephemeral wetlands, related to ambient temperature and permafrost depth (Vulis et al. 2021). Although shrinking, appearance or loss of water bodies does not classify as a tipping event in the very strict sense, i.e. there is not obvious strong, self-reinforcing factors involved, it still is a climate driven result of climate change with potentially large, widespread and irreversible consequences.*

At the end of the increased DOM TP section, the authors conclude that there should be 2 TP considered: one to anoxia. How is this related to the TP eutrophication related anoxia? is it the same or different?

*Response: In principle it is the same, however the resulting internal P-loading is generally more prevalent in eutrophic lakes, but increased GHG-emissions will be the likely result in both cases. We have added clarification; L 344-349: If it eventually leads to oxygen depletion and cascading feedbacks then it would qualify as a tipping point. However, there would be a time delay between the two events, with the latter being the critical tipping event. The deep-water anoxia would in principle cause the same effects as in eutrophic lakes. the resulting internal P-loading is generally more prevalent in eutrophic lakes, but increased GHG-emissions will be the likely result in both cases.*

The feedbacks to the climate for the eutrophication and DOM TP could be made more clear.

I found the two paragraphs on it quite dense and hard to follow. It would be good to explicit describe the feedbacks between the climate and the lake ecosystems.

*Response: We have elaborated and clarified in the revised ms. Both in the introduction, the main text and the discussion, we now explicitly address why decrease in oxygen and increase in organic C and nutrients entail increased GHG-emissions*

Lastly, the text needs careful reading for syntax and typos.

*Response: We thank the reviewer for picking up on this. We have conducted a thorough check for syntax and typos.*