Authors reply in bold red

Referee #2

General comments to the Author:

Sirota et al. develop a comprehensive analysis of the dynamics of bottom lake oxygen conditions in Lake Tiefer See over the past 200 years. This is a significant and timely topic for lakes worldwide, as long-term quantitative extents, causes, and consequences of hypoxia on e.g. the carbon burial efficiency, are still not fully understood. The authors rely on a spatial approach based on the analysis of multiple cores retrieved from different water depths, coupled with a multi-proxy approach, including chironomids, TOC, Mn:Fe ratios, δ13C, and varve preservation.

The sedimentological and geochemical analysis are sounds and exhaustive. The authors have invested considerable effort in providing a detailed description and analysis of the multiple cores.

Congruency in the multi proxies' responses strengthen conclusions on past hypoxia dynamics reconstruction in Lake Tiefer. Findings reveal a progressive alteration of the oxygenation conditions in the lake over the past two centuries, evidenced by an increased in the depth of hypoxia within the water column from 62 to 16 m. Furthermore, the authors highlight that the progressive spread of hypoxia has been associated with a series of transitions in the lake's geochemical and biological paleorecords, indicating varying sensitivities to hypoxia spread. This quantitative reconstruction thus sheds new light on the progression rhythms of hypoxia and provides valuable information on markers that can reconstruct hypoxia.

We thank the referee for his careful review and constructive comments. Below you find our detailed reply.

Below, Authors will find three main comments on the manuscript:

The objectives and raised questions are clearly outlined. However, limited attention is given to the drivers of hypoxia, despite it being stated as one of the study's objectives. The authors should either expand their efforts in this regard or consider removing the objective related to this aspect.

Objective 3 was revised and the discussion in this regard was elaborated in lines 528-538.

Robust dating is essential for high-resolution environmental reconstructions. Although this study presents three different dating methods, the connection to previous work on sedimentary dating using absolute methods should be more clearly stated. Specifically, radionuclide varve chronology has already been validated by 12 radiocarbon dates of organic macroremains (Brauer et al. 2019 https://doi.org/10.5194/deuquasp-2-89-2019, 2019). This earlier study reinforces confidence in the varve dating approach proposed here and should be more explicitly highlighted before using varves as dating approach (i.e. method and results section).

Agreed, see edition in methods section 3.3.1. Note that previous dating was done only for one depocentral core, and in this study, we expand varve counting and tephrochronology to additional cores to achieve a better spatial coverage.

The authors note that a decline in organic carbon degradation is observed as D13C decreases. This decrease could also be linked to a shift in carbon sources, towards e.g. a greater contribution from in-lake productivity. This would align with the concomitent increased fluxes in diatom frustules and biogenic calcite precipitation observed in the record. I am curious if the authors may have

underestimated the role of primary production associated with cultural eutrophication in the initiation of hypoxia and the subsequent preservation of varves (L 445).

Indeed, this is a main issue when dealing with organic matter content in lacustrine records. This is now clearer along the text in the introduction (lines 60-63 and lines 124-125) and discussion (lines 513-520). Our conclusion that a decline in OM degradation is observed along the cores is based on two arguments: 1. In our analyses, as well as along the Holocene record of the lake the TOC/TN ratio is ~10, typical to the ratio of lacustrine primary productivity. For comparison, the TOC/TN ratio of terrestrial OM is ~40, thus this lake does not experience a substantial OM external contribution (Drager et al., 2019). This agrees with the fact that there is no river inflow to the lake. 2. The D13C of the OM along the Holocene record ranges from -28 during non-varved intervals (oxygenated conditions) to -32 during varved intervals (hypoxic conditions). The fact that varved intervals which reflect hypoxic conditions are also characterized with D13C that characterize less degraded OM at different stages during the Holocene indicate that the sources of OM (lacustrine primary productivity) in the lake stay the same over time. Thus, the starting point of the D13C value of the OM is constant, while the actual value that is measured along the cores depends on the degree of OM degradation that shift those values.

Dräger, N., Plessen, B., Kienel, U., Słowiński, M., Ramisch, A., Tjallingii, R., ... & Brauer, A. (2019). Hypolimnetic oxygen conditions influence varve preservation and δ 13 C of sediment organic matter in Lake Tiefer See, NE Germany. Journal of paleolimnology, 62, 181-194.

Specific comments

I'm uncertain about 'Lake Tiefer See,' but as it is presented, it seems redundant to me. Perhaps just 'Tiefer Lake' or 'Tiefer See' would work?

We use the lake Tiefer See or TSK (Tiefer See klocksin) throughout the text. This is the correct form.

Abstract L13 : prefer “a detailed quantification of hypoxia spread on centennial timescales remained largely unquantified” to “a detailed quantification of hypoxia spread remained largely unquantified”. Note that recent synthesis on DO trends based on linological records provide quantification of hypoxia spread (e.g. Jane et al,. Nature 2021)

Implemented. This is an important paper in the topic and it is now referenced in the manuscript. Jane et al. (2021) do not focus on a single lake, but they integrate limnological data (temperature and oxygen measurements) from hundreds of lakes and show trends in their properties. Moreover, they do not study hypoxia from the sedimentological aspect.

L15: “associated with“ instead of “associated by“?

Corrected.

L17: “in 1997±1” instead of “at 1997±1”

Corrected.

L17: “and reached a lake-floor depth of 16 m at 1997±1” : is that the maximum extent record? Clarify

Clarified in the section 5.4 of the discussion. The core from 16 m depth is the shallowest core where varves, as a proxy for hypoxia were found at the top. At shallower lakefloor depth, ~11 m,

no varves were found, thus hypoxia did not prevail there. From this reason, we can follow the spread of hypoxia based on this sedimentological evidence.

L20: “threshold for hypoxia” Threshold for what? Varve onset? Death of macro benthic lives?

The onset of varve preservation marks the stop of bioturbation activity due to the death of bioturbating benthic life. In this case this happens because of the DO decline. Here we quantify the DO value (threshold), i.e., intensity and duration, in which below it the varve preservation is achieved.

This is now better explained in the text (lines 20-21).

L22: “depletion in DO started several decades prior to the varve preservation” Do you mean DO decline? drop below a certain DO threshold ?

Varve preservation is achieved as oxygen level drop to below a certain threshold which we quantify in this paper. However, the start of oxygen decline occurs earlier as indicated by the geochemical proxies. Clarified in Line 22.

L23: “accomplished” maybe change to something else, e.g. “started”

Revised

L34: “natural and anthropogenic processes”. Not sure you want to use “processes”, maybe “pressure” instead

Implemented.

L36: “decreased lake circulation” Do you mean water residence time? Winter mixing? Else?

Mixing.

L39-40: this is a bit of a shortcut. Burial of OM compensate part (not totally) of the C emissions to the atmosphere, in that sense those fluxes are important but it is a bit to exaggerated to say that it contributes to substantial contribution to the global carbon fixation (it is currently ~<0.1Pg/a, far below the anthropic emissions), maybe on geological timescale, not on annual basis…

Agreed, I added the time scale in Line 40. we cannot claim the increase in organic C fixation in lake sediments compensate the anthropogenic emission. It is just referring to the change in organic C fixation in lake sediments under changing oxygenated conditions on short geological time scales (100s-1000s years). Note, that in the text we state that this is compared with oceanic organic C fixation.

L44: Be more specific on your motivation

Revised in lines 45-46

L50: “[…] while non-laminated intervals reflect DO level sufficient for the existence of bioturbation organisms.” This is only accurate for lakes with a seasonally contrasted sedimentation regime.

This is written in general, and I think that any type of fine lamination (sub-mm to mm), no matter what is time scale represented by the lamination, will emphasize the absence of bioturbation. Moreover, seasonal lamination is highly common in lakes.

L54 : “Limited oxygen availability for laminated sediment intervals” not clear… Low oxygen conditions in bottom waters leading to varve preservation…?

The sentence was rephrased

L56: “OM degradation results in selective degradation of organic compounds with a more negative $\delta 13C$ composition and explains the more negative $\delta\ Corg$ 13 values measured in laminated sediments” Could you verify this statement. $\delta^{13}C$ values can result from various factors, such as the sources of organic matter, metabolic transformations, and biological fractionation… Worth stating why $\delta^{13}C$ can be specifically used in Lake Tiefer as OM degradation indicator.

Indeed. This is now better explained in the discussion 5.2 section (lines 513-520). See detailed response to this issue in your third main comment above.

L76 : why mesotrophic lakes only? The method can work also in oligo or eu-trophic lakes…

This is true and was deleted.

L120: Authors state 2 independent proxies of hypoxia while 3 proxies are presented… Please clarify this.

Revised.

L135: I suggest to add a statement to explain why the thin sections are made for. This is explain in the next sections but a statement there may help the reading.

Revised (line 150-151).

L396 : DO is not controlled by the hydrodynamics but also by oxygen consumption rates (i.e. biological and chemical DO demand).

Sentence was rephrased.

Important finding to me is that the thermocline depth limits the spread of hypoxia in Lake Tiefer. Should be more emphasised in the MS

Elaborated in lines 473-478.

L459 : Authors indicate a « two-step DO depletion in the lake ”. Decrease in DO can be progressive, triggering step by step impacts on the biogeochemical records. The steps are more relative to the impact of DO decrease on the sediment records than on DO trends itself… ?

This is true. The decrease in DO level is probably progressive, but this is indicated by two transitions in the sediments driven by changes in oxygen level. We can guess that between the start in DO decline (Units B-G transition) until it achieves the threshold for varve preservation, which is marked by the onset of varve preservation, the oxygen declines progressively. However, as a sedimentological study we think that we should describe the processes from the sedimentological point of view and from the observations that it provides.