General Comments

- Overall, this is a well-written and important contribution to our understanding of changing ecosystem functioning in lakes. It provides new insight by both developing projections of biogeochemical variables like phytoplankton dynamics and a novel comparison of the relative change in timing of important limnological events. The methods and results are clearly presented and the research is well contextualized. I suggest a few improvements below to better present the research in the context of other studies and research within the field of limnology.

We thank the reviewer for the kind comments and for their useful suggestions, which allowed us to clarify and improve the manuscript. We respond to each comment below, with our responses in text boxes and proposed additions to the text in red. Added references are given at the end of our reply.

Specific Comments

- 1A If you're not limited by words already, consider adding a sentence in the abstract that states how well your model did during training/validation to add support to the validity of your projections

We will add the following sentence to the Abstract, related to the model performance:

L. 18: Although the model explained only part of the variation in these events, the overall patterns were simulated with little bias.

- 1B In the first few sentences of the intro, can you add some language to make it crystal clear whether the studies you are citing demonstrated *already observed* changes or projections in timing of processes? On a glance, I think most of the studies you cite are observed already and adding a short paragraph that more thoroughly summarizes findings from other projection studies would help highlight the novelty of your approach (including phytos and catchment loading and comparing relative changes in annual timing events across multiple variables)

We will add a sentence with additional projection studies to link past observations to future projections:

L. 31: Moreover, trends in stratification, ice cover, and plankton phenology are likely to continue under future climate warming (Woolway et al., 2021; Feldbauer et al., 2022; Gronchi et al., 2023).

- 1C I think you are using spring 'metrics', 'events', 'processes' interchangeably to refer to your four response variables in the intro—might be good to choose one and stick with that

This is a valid comment and in line with comment 2C of Reviewer 2. When referring to the four spring events (ice-off, onset stratification, etc.), we will now consistently use the term “events”.

- 1D You introduce some really good, but new, content in the last paragraph of the intro (line 59 on) about why relative differences in the timing of spring events matters. I wonder if you could make this its own paragraph before you introduce your study and hypotheses so that you can expand a bit more on why relative shifts in timing matter—this is the key finding from your study so it should be emphasized heavily in the intro

We agree that it’s beneficial to highlight the importance of relative shifts in timing more. We will add a new paragraph to the introduction and include some additional ways in which relative shifts could matter. Moreover, we will restructure the last paragraph in response to comments from Reviewer 2, so that the Introduction ends with aims and hypotheses, instead of new content.

*Add after L. 51:* An earlier occurrence of spring events has several major consequences for lakes, but relative shifts could also result in previously unforeseen ecosystem effects, as biogeochemical cycles can shift and ecological niches may close or open due to changing time windows. For example, the timing of (spring) discharge in relation to the onset of stratification may partially determine where external nutrients end up in the water column (Fink et al., 2016; Cortés et al., 2017) and therefore their fate during the growing season. A longer gap between ice-off and the onset of stratification would alter mixing conditions early in the year, with corresponding changes in phytoplankton composition (Winder and Sommer, 2012). If phytoplankton growth is reliant on inflow of external nutrients, a shift towards earlier inflow, to periods with unfavourable light conditions for growth, might affect the intensity of a spring phytoplankton bloom (Hrycik et al., 2021), with consequences for higher trophic levels as well.

- 1E You might want to add a citation in the introduction somewhere to Adrian et al. 2012 who discuss how changes in climate drivers during key time periods are critical to informing overall ecosystem function: Adrian, R., Gerten, D., Huber, V. *et al.*Windows of change: temporal scale of analysis is decisive to detect ecosystem responses to climate change. *Mar Biol* **159**, 2533–2542 (2012). https://doi.org/10.1007/s00227-012-1938-1

This is indeed a relevant reference for the importance of critical events and their effects later in the season; thank you for this suggestion! We will now cite it to support our statements in the Introduction.

- 1F Line 42: I suggest remove ‘in this study’ phrasing and focus on why these metrics are important generally in this paragraph before you emphasize the details of your study specifically

We will remove the phrase “In this study” and add several sentences to the Introduction that outline the importance of the four events under study.

*Add after L. 44:* Ice-off is relevant for instance for its role in water column light availability, and a renewed exchange between water and atmosphere in general. Spring discharge can be an important source of external nutrients in catchments with significant snow or ice components. The spring phytoplankton bloom marks the start of the growing season, provides food for higher trophic levels, and influences nutrient and oxygen concentrations. The onset of stratification is a key event as well, and controls distribution of substances in the water column and affects, amongst others, oxygen, nutrient, and phytoplankton dynamics until stratification breakdown in autumn.

- 1G Methods, line 97-102: can you provide reference to any other studies which use biogeochemical process models and have similar R2 for reproducing observations? I’m not implying that the fit isn’t good enough, just that comparing to what others have done would be helpful to justify some of the lower R2 values

We will add references to three studies, which reported a similar goodness-of-fit for biogeochemical variables, also using coupled physical-biogeochemical models.

L. 102: This model performance for biogeochemical variables was in a similar range as previous studies (e.g. Chen et al., 2020; Kong et al., 2022; Zhan et al., 2023).

- 1H Line 108: can you provide a date range for the historical record of ice-off dates? Also in this section, can you report the bias for your 2C threshold for simulating ice-off for comparison since you report the error using the ice module?

A date range will be provided for ice-off dates and the MAE and ME will be also reported for the ice-off calculation with the temperature threshold.

New L. 108: Ice-off dates in the lake were recorded when the majority of the lake had thawed (earliest in 2000-2022 record: February 8; latest: April 26; median: April 4).

New L. 112: Multiple thresholds were tested with intervals of 0.5 °C and we settled on 2 °C, which showed the lowest bias (mean absolute error 12 days, mean error 2 days).

- 1I Line 145: include a citation for your workflow here as well?

Thank you for this suggestion: we will add the citation for the workflow.

New L. 145: All analyses were done in R version 4.1.3 (R Core Team, 2022) and forcing files, scripts, and model setups are provided by Mesman et al. (2023).

- 1J Line 148-149: a sentence similar to this would add strength to the abstract in demonstrating that your model performed well against observations. I would suggest adding the years of this calibration/validation time period here (not necessary for abstract though I think)

In line with comment 1A, we will add a sentence to the abstract.

L. 18: Although the model explained only part of the variation in these events, the overall patterns were simulated with little bias.

We decided to not split the results between calibration and validation period in the text. The percentage of events with an error less than 10 days was in fact the same for calibration and validation, but as can be seen in Figure 2, there were clear differences between the variables, so such a statement might give a wrong impression. Moreover, the number of years was necessarily limited and the validation period contained a small number of years, so we preferred to report the results for the whole period together. Figure 2 allows the reader to assess each variable and period separately.

- 1K Results, line 170: maybe just me, but I'm not familiar with the term 'shoal'. Could you rephrase as 'increase' or 'decrease'?

The term is indeed not used often; we will now use "become shallower" instead.

- 1L Table 1: Is there a way you could visualize this rather than providing a table (but perhaps keep table in SI)? I'm envisioning something similar to Figure 2 where you show the difference between the value at the beginning of the simulation (intercept) and the mean value at the end of the projection time period based on Sen's slope? This would allow you to highlight the directionality and magnitude of average change

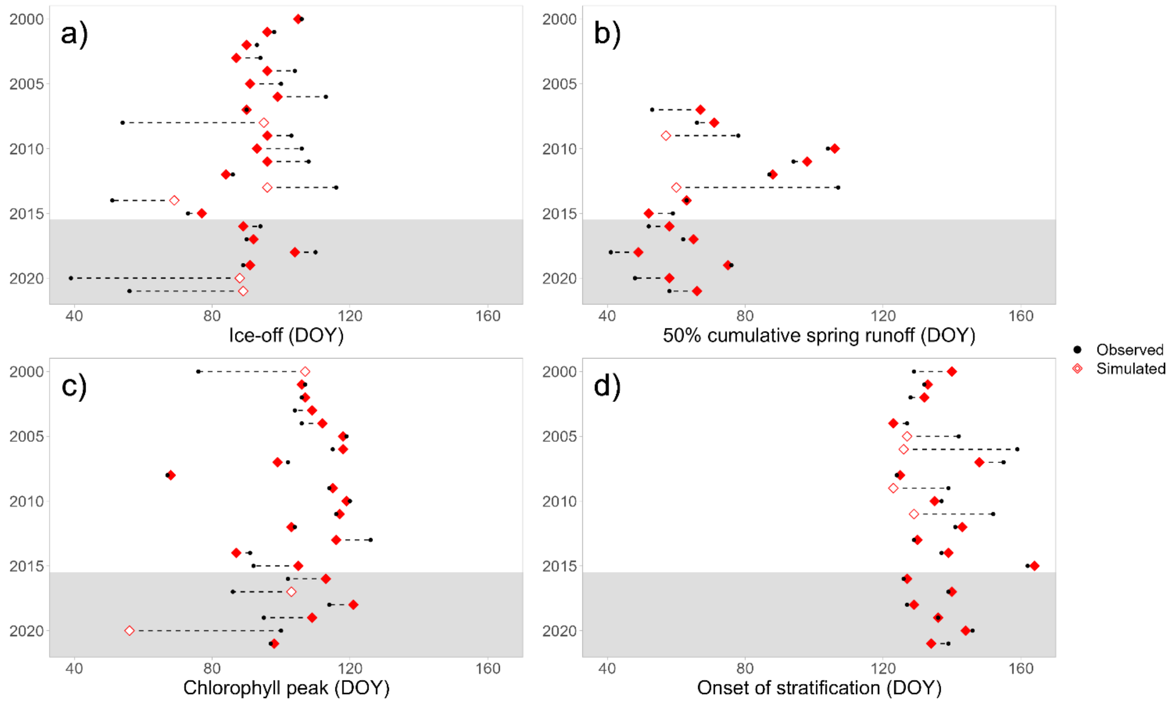
We agree that a visualisation is often more intuitive than a table for readers, but we preferred to leave the table as is, because a) the table contains a large number of variables, and not all are the main focus of the paper, and b) each variable has different units, which would complicate a figure.

- 1M Figure 2: can you make the font size overall a bit larger? It is necessary for me to zoom in quite a bit to read it as is. Would also suggest adding panel labels if this is a journal requirement. Instead of the purple square, maybe could you make the red diamonds open for years with a bad fit, filled for years with a good fit? The square is a little distracting (not a major issue though)

We were indeed struggling with how to represent the badly-fitted years in the plot, and we really liked the idea of using open and closed diamonds for this. Thank you for this suggestion! We will additionally add panel labels.

The small font size was an oversight, for which we apologise. This will be improved as well in the new Figure 2. The script in the workflow will be updated accordingly.

New Figure 2:




Caption Figure 2. Simulated (red diamonds) and observed (black circles) timing of (a) ice-off, (b) 50% cumulative spring runoff, (c) spring chlorophyll peak, and (d) onset of stratification. The years are on the y-axis, and the difference in timing is shown by a dashed line. The units on the x-axis are in day-of-year (DOY). The light grey area indicates the validation period. Open diamonds denote the years that were fitted badly (> 14 days error) and that are further investigated in Supplement section S2.

- 1N Line 215: is there a figure you can reference to support this? As it's written, it's unclear if you mean under current conditions or under future projections

Also in response to Reviewer 2's comment 2J, we will clarify the sentence and refer to Figure 2 and two references.

New L. 215: In Lake Erken, spring phytoplankton growth is not reliant on stratification due to the limited mean depth of the lake, and the spring chlorophyll peak (dominated by diatoms) tends to occur prior to onset of stratification (Figure 2; Weyhenmeyer et al., 1999; Moras et al., 2019), …

- 1O Line 245: this is really interesting. Did you calculate chlorophyll-a concentrations later in the growing season or just spring? I am wondering if there is an antecedent effect for later in the year which could have broader implications for additional bloom events and could be useful to add to the discussion

We focus in our study on the spring period, but have model output for the whole year. If the lower spring peak was indeed caused by a gradual shift to more light limitation compared to nutrient limitation (L. 220-221), while nutrient inputs stayed the same, one could expect a "broader" rather than "higher" spring peak, and this could have implications later in the season. It would be difficult to assess whether there would be causal links in our current model setup, however, and this would require additional experiments that would distract from the main message in the paper. However, also in response to Reviewer 2's comment 2A, we add a section to the Discussion on effects of spring events beyond spring itself.

*Add after L. 224:* These absolute changes in the timing of spring events may lead to several changes in lake state (Figure 5 *(an added diagram based on Reviewer 2's comment 2A)*). For instance, the earlier spring chlorophyll peak leads to an earlier uptake of nutrients and a longer growing season. However, not all effects are restricted to spring itself. An earlier onset of stratification leads to lower hypolimnetic oxygen concentrations in the summer (Jane et al., 2023) and a longer period of nutrient limitation in the epilimnion (Sommer et al., 2012). These trends were indeed seen in our future projections, with chlorophyll and epilimnetic nitrate concentrations remaining constant despite increased nutrient loading (Jiménez-Navarro et al., 2023), and were likely partially driven by the earlier stratification onset.

- 1P Line 272: I think you should emphasize that this is especially true for biological responses like chla (there are studies looking at multiple connected hydrodynamic processes, Ayala et al. 2020, Barbosa et al. 2021, Feldbauer et al. 2022, Desgue-Itier et al. 2023, Wynne et al. 2023, etc.)

We agree, and will add a phrase that stresses the novelty of also looking into biological and watershed responses. The most notable exception of biological processes studied in conjunction would be phytoplankton-zooplankton phenology, which may not have been apparent in our Introduction, so we added a sentence about this as well.

L. 41: The coupled phenology of phytoplankton and zooplankton is rather well-studied (Sommer et al., 2012), but timing of other events is often studied in isolation, or restricted to seasonality in lake physical processes (ice cover and stratification).

New L. 270-272: Phenological changes in individual lake events in response to climate change have been well-established, but relative changes and future projections of the timing of multiple interdependent processes events in the same lake, extending to biological and watershed responses, have received little attention so far.

- 1Q I think the study could benefit from more discussion of the implicit assumptions from focusing on spring event timing as your response variables (e.g., instead of summer, winter, or fall events). You do a good job justifying why spring is important (and I believe it), but I think you could add context which highlights other research which shows that antecedent conditions during other time periods (e.g., winter-time dynamics, storm events) are important for year-round functioning and adding some context to acknowledge this would be helpful in the discussion. Some potential citations

- Cavaliere et al. 2021 https://doi.org/10.1029/2020JG006165
- Adrian et al. 2012 https://doi.org/10.1007/s00227-012-1938-1
- Thayne et al. 2021: https://aslopubs.onlinelibrary.wiley.com/doi/full/10.1002/lno.11859

We add context regarding critical timing windows and antecedent conditions in other parts of the year, as suggested. We will mention storms, the occurrence of autumn blooms, and the effects of incomplete mixing in winter. We mention this in the Introduction, before going deeper into springtime events.

*Add after L. 35:* Events during critical time windows, and the antecedent lake conditions during these periods, are highly relevant throughout the year, and effects may persist beyond the event itself (Adrian et al., 2012). For instance, antecedent lake conditions preceding storms may be more important than storm characteristics themselves to determine storm effects (Thayne et al., 2021), and autumn phytoplankton blooms may or may not trigger depending on mixing conditions during turnover (Findlay et al., 2006), which may again affect phytoplankton composition in the following spring (Yang et al., 2016a). Incomplete winter mixing, due to warm winter temperatures or mild winds, affects oxygen conditions in following years (Schwefel et al., 2016).

Additional references, not previously cited in manuscript:


Adrian, R., Gerten, D., Huber, V., Wagner, C., and Schmidt, S. R.: Windows of change: temporal scale of analysis is decisive to detect ecosystem responses to climate change, Marine biology, 159, 2533-2542, 10.1007/s00227-012-1938-1, 2012.

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Gronchi, E., Straile, D., Diehl, S., Jöhnk, K. D., and Peeters, F.: Impact of climate warming on phenological asynchrony of plankton dynamics across Europe, Ecology Letters, 26, 717-728, 10.1111/ele.14190, 2023.

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Winder, M. and Sommer, U.: Phytoplankton response to a changing climate, Hydrobiologia, 698, 5-16, 10.1007/s10750-012-1149-2, 2012.

Yang, Y., Stenger-Kovács, C., Padisák, J., and Pettersson, K.: Effects of winter severity on spring phytoplankton development in a temperate lake (Lake Erken, Sweden), Hydrobiologia, 780, 47-57, 10.1007/s10750-016-2777-8, 2016a.

Zhan, Q., de Senerpont Domis, L. N., Lürling, M., Marcé, R., Heuts, T. S., and Teurlincx, S.: Process-based modeling for ecosystem service provisioning: Non-linear responses to restoration efforts in a quarry lake under climate change, J Environ Manage, 348, 119163, 10.1016/j.jenvman.2023.119163, 2023.