**Response to Anonymous Referee #2**

We would like to thank the referee for taking the time to review our manuscript and for their comments. We have included the reviewer comments below along with our responses.

***Reviewer comment:*** Richter et al. reconstruct cold-season temperature trends over the last 2 ky for south- west Iceland using alkenones produced by lacustrine haptophyte algae. The authors demonstrate that alkenones from lake VGHV record a long-term warming trend, as well as decadal to centennial scale variability within the long-term trend. They couple this temperature reconstruction with a lake energy balance model to support that increasing high-latitude winter insolation is likely responsible for the overarching cold-season warming for the last ~2 ky, while climate perturbations are likely responsible for high frequency variability in proxy data. The authors contextualize this data in a broader framework by suggesting that this dataset, and more studies like it, could help consolidate discrepancies between global climate model output and proxy reconstructions for the northern hemisphere through the Holocene. Major contributions of this manuscript:

This work offers important insight into seasonal differences in temperature for SW Iceland (and by inference this part of the N Atlantic) for the last 2 ky

The coupling of proxy inference and lake energy model is a progressive approach for interpreting proxy data by testing it within varying climate forcing scenarios

The presentation of the data is thoughtful and clear

Criticisms of the manuscript:

I find the discussion around the seasonality of this proxy, and the conclusions drawn from it, to be somewhat confusing and at times inconsistent. I think it would be helpful if the manuscript more clearly articulated the chain of logic/evidence that provides that alkenones, which are stated to bloom in spring, can be interpreted more broadly as a record of cold-season temperatures driven by cold-season insolation.

Within this point, I would find it helpful if the background discussion around the proxy touched on the fidelity of alkenones for reconstructing temperature (is it known to have significant error associated with it, or low significance values?) and are there calibration data that covers a climatically similar region? I appreciate that this record is being interpreted qualitatively and it is clearly stated in the manuscript that there is no local calibration data, but I think it would improve confidence in this interpretation of the data to know that it has been tested/utilized in comparable locations, particularly in interpreting high frequency changes as related to climate perturbations and not stochastic proxy noise

***Response:*** We will update the manuscript to include a discussion of previous Group I alkenone calibrations, their fidelity, and previous downcore records as discussed below.

Group I Isochrysidales and their corresponding alkenones have, so far, only been identified in Northern Hemisphere lakes at latitudes ranging from 42-81°N (Longo et al., 2018). The Northern Hemisphere lake calibration for Group I alkenones, which includes VGHV and was developed using the average temperature of the four months centered around the spring isotherm for each lake ($U^{K}_{37} = 0.029T\text{-}0.49$, $r^2 = 0.60$), has an RMSE = ± 1.69°C (Longo et al., 2018). An updated calibration for Group I that includes additional lakes in northeastern China ($U^K_{37}$ = 0.030*T*-0.479, $r^2$ = 0.0479) has an RMSE = ± 1.71°C (Yao et al., 2019). Group I alkenone calibrations also exist for Lake BrayaSø in Greenland ($U^K_{37}$ = 0.0245*T*-0.779, $r^2$ = 0.96, note the calibration also includes data from several German lakes, see Zink et al., 2001; D'Andrea et al., 2011), Lake Kongressvatnet in Svalbard ($U^K_{37}$ = 0.0255*T*-0.804, $r^2$ = 0.85, D'Andrea et al., 2012), Toolik Lake in Alaska ($U^K_{37}$ = 0.021*T*-0.68, $r^2$ = 0.85; Longo et al., 2016), and Vikvatnet in Norway ($U^K_{37}$ = 0.0284*T*-0.655, $r^2$ = 0.94; D'Andrea et al., 2016). A key argument linking our data to winter conditions is that the haptophyte bloom time may be fixed by the annual cycle by processes such as the photoperiod, such that blooms may develop in the very early stages of ice-off. As discussed in the paper, the timing of ice-off is set in part by winter conditions and partly by early spring temperatures (which we refer to in the text as "winter-spring"). Thus, although the haptophyte bloom occurs in spring, spring lake temperatures are set in part by winter temperatures. Our modeling work supports the seasonal dependence of spring temperatures at our study site. We will elaborate on these points in the text and we will modify Figure A2 to include the standard error for each calibration that is plotted.

There are only a few studies that have applied Group I alkenones to downcore records. A 16,000-year reconstruction of winter-spring (DJFMAM) temperatures was developed using Group I alkenones for Lake E5 in Northern Alaska, and also exhibits gradual warming throughout the middle to late Holocene in response to increasing winter-spring insolation, greenhouse gases, and regional feedbacks (Longo et al., 2020). Temperature reconstructions with a comparable resolution to our record include reconstructions from Lake BrayaSø in Greenland that spans c. 5,600 yrs BP (resolution c. 7-90 yrs, D'Andrea et al., 2011) and Kongressvatnet in Svalbard that spans 1,800 yrs BP (resolution 4-30 yrs, D'Andrea et al., 2012). In both studies, the Group I alkenone records are interpreted as summer (JJA) temperature reconstructions due to the very late ice-off dates in these regions (D'Andrea et al., 2011, 2012). The amplitudes of the temperature changes observed in the temperature records from Greenland (temperatures range from 3°C to 9°C to between 10 CE and 1999 CE; D'Andrea et al., 2011) and Svalbard (temperatures range from 2°C to 6°C between 230 CE and 2009 CE; D'Andrea et al., 2012) are smaller in magnitude than the estimated temperature change in our record using $U^K_{37}$ = 0.029*T* (temperature range 20°C). The higher amplitudes observed in our reconstruction could be explained by the lack of a local calibration and that our record reflects variations in winter and spring temperatures rather than summer temperatures. We will modify our discussion to highlight the studies we just discussed.

***Reviewer comment:*** I would find it valuable to know if there is a competing effect from declining summer insolation/temperature on spring temperatures and the timing of ice-out. It's unclear if JJA/SON is held constant in the model, or if there is little response to ice-out date/water temps given changing temps/insolation during these seasons (Fig. 5).

***Response:*** As described in section 2.4, perturbations in insolation and temperature are applied to every season (DJF, MAM, JJA, and SON) to determine the effects of these seasonal perturbations on spring lake water temperatures and ice-out dates. In section 3.2 we find that the there is no competing effect of summer or fall insolation and air temperature on spring lake water temperatures and the timing of ice-out. More generally, winter temperatures at VGHV are always cold enough to freeze the lake surface, and because the minimum water temperature is always reached during the winter by this process, the summer climate has a small influence relative to early spring temperatures. Thereby, the seasonal lacustrine cycle effectively 'resets' the temperature each winter. We will modify sections 3.2 and 4.1 to make these points clearer.

***Reviewer comment:*** Is the lake model consistent with observational data for what controls lake ice-out dates & water temps? (i.e. are there examples in modern observational data of earlier ice-off dates in regions with increasing winter air temperatures?)

***Response:*** In a previous study, controls on lake ice-out dates and water temperatures were determined for Toolik Lake in Alaska and were validated using available monitoring data demonstrating that increasing winter air temperatures led to earlier ice-off dates (see Longo et al., 2020). However, it would be extremely challenging given the existing climatological data to validate the model at our study site. We do not attempt to quantitatively interpret the temperature data, so it is not entirely necessary for our study to perform this validation; our modeling work is focused on sensitivity tests.

***Reviewer comment:*** Some discussion around if the parameters & outputs of this model are climatically probable for the coverage of the record would improve this manuscript. E.g. An air temperature increase in the winter of +7 deg does dramatically move the ice-out date, but that change in temperature seems far too large for the amount of cold-season insolation change. These bounds, I think, are justified in lines 145-157, but I find this statement/constraint confusing. Observed temperatures in any given season can range by +/-7, but why would average cold-season temperatures range by this amount over the last 2 ky? Change in insolation seems to have much less impact in ice-out dates in the model (Fig 5) but is credited for driving trends in alkenone data. This reads as a mismatch in results-conclusions as written, and the manuscript would improve from some text that consolidates the results of the model with their interpretation of the data.

***Response:*** We will modify section 2.4 to elaborate on the temperature bounds used in the lake model as discussed below.

The temperature perturbations of the lake model are used to determine the sensitivity of lake water temperatures and ice-off dates to seasonal changes in temperature, and thereby confirm the seasonality of our proxy. The magnitude of the temperature perturbations used in the lake model are based on instrumental data at Hella station in Iceland (1958-2004, Icelandic Meteorological Office). Between 1958-2004 the range of mean seasonal temperatures are as follows: winter (DJF) -3.7°C to 1.8°C, spring (MAM) -1.0°C to 6.9°C, summer (JJA) 8.8°C to 12.0°C, and fall (SON) -1.3°C to 6.7°C. From year-to-year, ±7°C swings in mean seasonal temperatures, particularly during the transitional seasons, are reasonable based on the instrumental data. Further, we use these large changes in temperature to demonstrate that large fluctuations in summer and fall temperatures have a minimal influence on our proxy. We could certainly perform the sensitivity tests using a larger temperature range, but there is little constraint on where the bounds of that range might lie. We acknowledge that each of our samples represent an average temperature of 5-19 years and, based on the instrumental data, we would then expect seasonal air temperatures to change by ±3°C. However, as mentioned in our previous comment, reconstructions from Greenland and Svalbard with a similar resolution also report 4-6°C changes in temperature over the last c. 2,000 years (D'Andrea et al., 2011, 2012).

One of the goals of our study is to determine what might lead to a long-term increase in the winter-spring temperatures observed in our record. As demonstrated in our model, lake water temperatures are sensitive to both changes in air temperature and also directly respond to changes in shortwave radiation. Short-term and long-term changes in air temperatures can be attributed to multiple factors (i.e., shortwave radiation, greenhouse gases, and regional feedbacks), which, as demonstrated in the lake model, can either amplify or overprint the changes observed in the lake water temperatures at our study site. We will clarify these points in our discussion section.

***Reviewer comment:*** The warming trend apparent in this data really seems to start just before ~400 CE, with temperature values only returning to average values from the start of the record several centuries later. This could indicate the long-term trend is less pronounced than what is captured by this window (i.e. there is a rebounding from depressed temperatures, and then warming above that average only over the last millennia). I think it would be an interesting point to add to consider if the early values (0-200 CE) are the anomaly of the record, of if the record should be considered in the context of these early values.

***Response:*** Thank you for the interesting suggestion and we will include this in our discussion. To verify that the long-term trend is less pronounced than what is captured in the current window, we would need to extend our record beyond 0 CE. That will hopefully will be pursued in future studies either in VGHV or other nearby sites in Iceland that contain Group I alkenones.

***Reviewer comment:*** Overall I think this is a significant and important study, but the manuscript would benefit from some additions to background information and from adding text that consolidates what is learned in the model with their proxy data, and the climate implications of these data, so that it is very clear the conclusions are supported by their data prior to publication.

***Response:*** Thank you, and we hope that the changes we outline above address this comment.

**References**


D'Andrea, W. J., Huang, Y., Fritz, S. C., and Anderson, N. J.: Abrupt Holocene climate change as an important factor for human migration in West Greenland. Proc. Natl. Acad. Sci., 108, 9765-9769, https://doi.org/10.1073/pnas.1101708108, 2011.

D'Andrea, W. J., Vaillencourt, D. A., Balascio, N. L., Werner, A., Roof, S. R., Retelle, M., and Bradley, R. S.: Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard. Geology, 40, 1007-1010, https://doi.org/10.1130/G33365.1, 2012.

D'Andrea, W. J., Theroux, S., Bradley, R. S., and Huang, X.: Does phylogeny control $U_{37}^{K}$ - temperature sensitivity? Implications for lacustrine alkenone paleothermometry. Geochim. Cosmochim. Acta, 175, 168-180, https://doi.org/10.1016/j.gca.2015.10.031, 2016.

Icelandic Meteorological Office: https://en.vedur.is/climatology/data/, last access: 11 June 2020.

Longo, W. M., Theroux, S., Giblin, A. E., Zheng, Y., Dillon, J. T., and Huang, Y.: Temperature calibration and phylogenetically distinct distributions for freshwater alkenones: evidence from northern Alaskan lakes. Geochim. Cosmochim. Ac., 180, 177-196, https://doi.org/10.1016/j.gca.2016.02.019, 2016.

Longo, W.M., Huang, Y., Yao, Y., Zhao, J., Giblin, A.E., Wang, X., Zech, R., Haberzettl, T., Jardillier, L., Toney, J., and Liu, Z.: Widespread occurrence of distinct alkenones from Group I haptophytes in freshwater lakes: Implications for paleotemperature and paleoenvironmental reconstructions. Earth Planet. Sci. Lett., 492, 239-250, https://doi.org/10.1016/j.epsl.2018.04.002, 2018.

Longo, W. M., Huang, Y., Russell, J. M., Morrill, C., Daniels, W. C., Giblin, A. E., and Crowther, J.: Insolation and greenhouse gases drove Holocene winter and spring warming in Arctic Alaska. Quat. Sci. Rev., 242, 2020.

Yao, Y., Zhao, J., Longo, W.M., Li, G., Wang, X., Vachula, R.S., Wang, K.J. and Huang, Y.: New insights into environmental controls on the occurrence and abundance of Group I alkenones and their paleoclimate applications: Evidence from volcanic lakes of northeastern China. Earth Planet. Sci. Lett., 527, 2019.

Zink, K. G., Leythaeuser, D., Melkonian, M., and Schwark, L.: Temperature dependency of long-chain alkenone distributions in recent to fossil limnic sediments and in lake waters. Geochim. Cosmochim. Acta, 65, 253-265, 2001.