Dear Bjørg Risebrobakken,

Thank you for taking the time to review our manuscript, we hope the edits that we outline below and that we made in the manuscript will address the comments.

Sincerely,
Nora Richter

Editor comment: Out of curiosity from reading your responses: You state e.g. that while you will discuss the relation to existing SST data, including the subsurface data by Harning, you are unsure of the relevance of subsurface temperatures. From a marine point of view I would find this comparison interesting with respect to your seasonality discussion, expecting the annual mean/winter/spring temperature development of the surface water to be reflected by the subsurface record. At least in the eastern Nordic Seas we see that the subsurface temperature is constant year round, comparable to the winter/spring surface temperatures (e.g. Nyland et al., 2006; Jansen et al., 2008; Andersson et al., 2010; Risebrobakken et al., 2011). Hence, I wonder if it is possible to use existing information with respect to seasonal responses from nearby marine records to strengthen your argumentation for seasonality impact on your records?

Response: Thank you for the comment. We included a discussion on nearby marine records and the seasonal responses in our manuscript (see section 4.1):

“SST reconstructions near southern Iceland show that surface temperatures either increased (Berner et al., 2008; Thornalley et al., 2009; Miettinen et al., 2012; Orme et al., 2018) or did not significantly change (Sicre et al., 2011; Van Nieuwenhove et al., 2018) over the last 2,000 years. Marine reconstructions of temperature from below the summer thermocline and bottom water record a decrease in mean annual temperatures over the Common Era (Thornalley et al., 2009; Ólafsdóttir et al., 2010; Moffa-Sánchez et al., 2014) as the transport of warm North Atlantic Current waters by the Irminger Current decreased over the last 2,000 years (Ólafsdóttir et al., 2010). Based on existing paleo- and historical records we conclude that sea ice feedbacks only play a minor role in driving long-term changes in winter and spring temperatures at our study site, whereas an increase in SSTs along the southern coast could contribute to the warming trend observed in our record. However, discrepancies in existing proxy records makes it difficult to correlate changes in SSTs to changes in winter and spring temperatures at VGHV.” (lines 292-301)

Response to Anonymous Referee #1

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 and edits to the manuscript (highlighted in blue).

Reviewer comment: Richter et al. present a temperature reconstruction for a season that is rarely captured by proxy archives. To do so, they apply an exciting emerging alkenone-based proxy (UK37) using an elaborate extraction and purification procedure. The authors build on a previously published robust chronological framework that allows them to confidently resolve shifts in multi-decadal climate conditions. I do, however, have a number of major concerns about the analysis and interpretation of this work:

The presented dataset suffers from species mixing, complicating its interpretation as a temperature record. Now, the authors use RIK37 cut-off values to exclude samples that are dominated by Group II haptophytes. As calibrations exist for this phylotype, a significant portion of their data points is excluded as a consequences of this rather crude solution. I would recommend the authors to calculate the RIK38E index to better differentiate phylogeny (mixing) and derive temperatures from Group II data.

Response: Developing a temperature calibration using the RIK_{38E} index would not resolve the issue of species mixing as both Group I and II Isochrysidales produce C_{38}Et alkenones (see Zheng et al., 2019). Further temperature calibrations for Group II vary for planktonic and benthic species (see D'Andrea et al., 2016). We decided to rely on C_{37}Me alkenones due to the low concentrations of C_{38}Et and C_{38}Me alkenones. Further, the U^{K}_{37} index was successfully applied to reconstruct temperature changes in other lakes containing Group I Isochrysidales (D'Andrea et al., 2011, 2012; van der Bilt et al., 2019; Harning et al., 2020; Longo et al., 2020).

Reviewer comment: I commend the authors for their efforts to better constrain the seasonality of haptophyte production (and temperature sensitivity), but have two concerns. First, ice-off dictates the timing of haptophyte blooms: with this in mind, I wonder why the authors did not rely on satellite data to validate the 30 yr control run outlined in section 2.4. High-res imagery is freely available for the entire period: if in agreement with model output, this would significantly strengthen the robustness of their approach. Secondly, the presented modelling results reveal that both late winter as well as spring season temperatures help determine ice-off dates: this does not justify presenting the record as a "cod season" reconstruction.

Response: Thank you for the suggestion, however, the purpose of performing the sensitivity studies with the lake model is to identify the main drivers that influence lake water temperatures during the spring season and, therefore, our proxy. Validating the exact date of spring ice-off would not alter the main conclusions of our study. Further, previous work has shown that the primary alkenone bloom likely begins prior to the exact ice-off date (Longo et al., 2018). We will clarify the points discussed above in the text of section 2.4.

We will change "cold season" to "winter and spring"/ "winter-spring" in our manuscript, where winter-spring is defined as December to May.

We have added the following sentences to section 2.4:

"Alkenone production starts prior to ice-off, then increases as the lake undergoes isothermal mixing, and decreases when thermal stratification begins to develop in late spring/early summer (Longo et al., 2018)." (lines 144-146)

"The purpose of the lake model was to determine the sensitivity of our proxy to different forcing mechanisms by assessing the magnitude of the temperature response and timing of ice-melt relative to our control simulation." (lines 150-152)

We changed "cold season" to "winter and spring"/ "winter-spring" in the manuscript.

Reviewer comment: See line 215: I think the wording is far too strong here. The authors argue existing calibrations provide "unreasonable" estimates and back this up with unrealistically high temperature values. They do, however, not state that these values were calculated using site-specific intercepts provided for each of the used calibrations while the authors of the applied calibrations advise against doing so. To remedy this, I advise the authors to discuss the relative temperature fluctuations plotted in Fig. A2(b): indeed, the magnitude of these swings are of equal magnitude as those observed during the spring transitional season (Fig. 5b).

Response: Thank you for the suggestion, we will modify section 3.3 to discuss the relative temperature fluctuations in Fig. A2(b).

Relative temperature changes determined using only the slope of the calibration for Group I still provide unrealistic temperature changes (for $U^K_{37} = 0.0219T$ the temperature range is 26.9°C). The slopes determined by D'Andrea et al. (2016) for Group III ($U^K_{37} = 0.0447T$) alkenone calibrations result in a smaller temperature range of 13.2°C and an estimated temperature change of 8°C from 250-350 CE to 1850-1950 CE.

We have modified section 3.3 as follows:

"The U^K_{37} index can provide temperature estimates using linear relationships that are calibrated in lakes with Group I alkenone-producers (D'Andrea et al. 2011, 2016; Longo et al., 2016, 2018). Existing temperature calibrations, except for the Northern Hemisphere calibration by Longo et al. (2018), for Group I are site-specific and therefore cannot be readily applied to VGHV (e.g. calibrations give estimates of 10.2 to 33.5 °C (D'Andrea et al., 2011), 7.1 to 34.4 °C (Longo et al., 2016), 4.4 to 24.5 °C (D'Andrea et al., 2016), -1.4 to 18.3 °C (calibration for Northern Hemisphere lakes by Longo et al., 2018; see Fig. A2). Most of the variation between sites is accounted for by the y-intercept of the calibration, so the slope of Group I calibrations was suggested as a better determinant of relative temperature changes for sites lacking a site-specific calibration (D'Andrea et al., 2016). However, the slopes determined for Group I calibrations still result in a very large and likely unreasonable temperature range of 26.9 °C for $U^K_{37} = 0.0219T$ (D'Andrea et al., 2016). The slope determined for Group III alkenone calibrations ($U^K_{37} = 0.0447T$; D'Andrea et al., 2016) provides a more reasonable temperature range of 13.2 °C and an estimated temperature change of 8 °C from 250-350 CE to 1850-1950 CE. Given the sensitivity of VGHV lake water temperatures to winter and spring season perturbations and the large variability in winter and spring temperatures observed in the instrumental data (mean temperatures in the winter and spring (DJFMAM) season range from -2.4 °C to 3.4 °C with a seasonal variance of 13.1 °C between 1958-2004 at Hella station; Icelandic Meteorological Office), it is plausible to observe temperature swings close to 10 °C during the spring transitional season

(Fig. 5b). However, the amplitude of reconstructed temperatures is still relatively large considering that each sample is an average of 5-19 years, and most likely stems from the lack of a local calibration. Nevertheless, the U^{K}_{37} index is known to be highly sensitive to temperatures in NH lakes, therefore we use the U^{K}_{37} index to infer and evaluate qualitative changes in temperature trends and variability during the past 2,000 years." (lines 231-249)

Reviewer comment: Paragraph around line 230: here the authors try to relate their reconstructions to warming/cooling periods that are often referenced in the (North Atlantic) literature. I would stay clear from this and consider removing this section for a number of reasons. First, a string of recent studies has underlined just how spatio-temporally heterogeneous expression of these events is (see e.g. Werner et al. 2018 – COP, McKay et al. 2018 –GRL, and van der Bilt et al. 2019 – QSR). Secondly, most of these events are most clearly expressed in summer, while the authors argue that their record captures "cold season" conditions. Finally, and related to this, the perceived correspondence is tenuous at best as the authors also confirm by using wording like "roughly coincides" or "could be associated".

Response: Thank you for the suggestion, we will modify the text in section 3.3 to only discuss changes in our record. However, part of our goal is to compare our record with existing warm season reconstructions. Although there is considerable spatio-temporal variability in major warm and cold events, it is still useful to highlight anomalous time periods defined by previous warm season reconstructions in Iceland and other regions in the Northern Hemisphere. Therefore, we think it is important to keep the comparisons with warm season reconstructions in section 4.2.

We modified the text in section 3.3 as follows:

"The U^{K}_{37} record from VGHV, corrected for species mixing, exhibits a long-term trend towards warmer spring lake water temperatures over the last 2,000 years as well as strong multi-decadal to centennial variability (Fig. 6). The gradual warming trend in our record begins after c. 400 CE. In particular, a warmer period occurs from the start of our record to c. 200 CE, followed by cooling from c. 250-600 CE. Temperature variability increases after c. 850 CE, and warmer periods occur between c. 850-1050 CE, c. 1100-1300 CE, and c. 1450-1550 CE. Relatively cooler periods occur at c. 1100-1200 CE, c. 1300-1450 CE, c. 1550-1750 CE, and c. 1850-1880 CE. However, caution should be used when interpreting results after c. 1400 CE because of low sampling resolution (c. 50 yrs between each sample)." (lines 251-257)

Reviewer comment: Section 4.1: please restructure and tighten this paragraph. As the presented record only covers the past 2millennia, I think the current full Holocene focus is not the right way to frame things. Also, the authors allude to the so-called "Holocene temperature Conundrum" but don's state so (or explain it clearly). The way I see things, the main message here is that spring temperatures are (not entirely surprisingly) not driven by changes in summer insolation. I would contextualize/strengthen this by discussing other non-summer temperature reconstructions (which the authors already do to some extent), and argue why one would expect to see this "cold season" imprint in a maritime Arctic setting like Iceland, where it is known that many feedbacks may overprint any radiative signature, notably surface ocean currents, but also sea-ice feedbacks – in this respect, I recommend the authors to check Park et al. 2019 – Science Advances.

Response: Thank you for the suggestion, we will modify the text to explain the Holocene temperature conundrum and discuss the forcings that are relevant for the last 2,000 years. As mentioned by the reviewer, radiative forcings may be overprinted by sea-ice feedbacks and circulation changes, however as we will fully discuss in the modified manuscript, this is not necessarily the case.

With regards to sea-ice feedbacks (Park et al., 2019), sea ice normally only occurs off the coast of northern Iceland, and therefore has a stronger influence on climate in northern Iceland relative to southern Iceland (Ogilvie, 1984; Ogilvie & Jónsson, 2001; Hanna et al., 2004). This observation is consistent with results from the study on mid-Holocene temperature changes in response to sea ice loss by Park et al. (2019): note the significantly lower SST response to Arctic sea ice loss (Fig. 3d) along the southern coast of Iceland (0.2 K) relative to northern Iceland (0.8 K) in the results from the mid-Holocene simulation. We will modify section 4.1 to discuss these points in more detail.

As mentioned by the reviewer, the close proximity of VGHV to the coast means that air temperatures at VGHV are also influenced by changes in sea surface temperatures (SSTs; Hanna et al., 2006). In particular, the Irminger Current, a branch of the northward moving warm waters of the North Atlantic, is advected clockwise along the southern and western coast of Iceland (e.g. Daniault et al., 2016). However, reconstructions of subpolar North Atlantic Current SSTs show diverging trends over the last 2,000 years with varying degrees of centennial to millennial variability, most likely reflecting differences in proxy seasonality (see Moffa-Sánchez et al., 2019). This makes it difficult to assess how SSTs have contributed to changes in winter and spring temperatures at VGHV, but as rightly stated by the reviewer, should not be ruled out. We will modify discussion section 4.1 to highlight the points we just discussed.

We modified section 4.1 as follows:

"Mean annual temperature syntheses from the NH exhibit a long-term cooling trend over the last 2,000 years (Kaufman et al., 2009; PAGES 2K Consortium, 2013, 2019) that is often interpreted as a response to decreasing summer insolation (Kaufman et al., 2009) and/or increased volcanic activity during the LIA (Miller et al., 2012). Climate model simulations suggest that solar variability acts as a secondary source of variability and land use changes may be important for explaining some of the changes in NH surface temperatures between the MCA and LIA, whereas increases in greenhouse gases remain stable until the late 19th century (Otto-Bliesner et al., 2016). The magnitude of the cooling trend and centennial and multi-decadal changes differs among global temperature reconstructions (PAGES 2K Consortium, 2019) and is often larger in NH temperature reconstructions compared to climate model simulations (Rehfeld et al., 2016; Ljungqvist et al., 2019). The discrepancies in temperature reconstructions and climate models could stem from a warm season bias in NH proxy reconstructions, leading to an overestimation of changes in mean annual and cold season temperatures in proxy reconstructions compared to climate model simulations (Liu et al., 2014; Rehfeld et al., 2016; PAGES 2K Consortium, 2019)." (lines 260-270)

"Iceland has a maritime climate and also sits near the edge of the Arctic sea ice; therefore, air temperatures are sensitive to regional sea-ice feedbacks and variations in sea surface temperatures (SSTs). The VGHV temperature record shows that winter and spring air temperatures warmed over the last millennium, whereas temperature and sea ice reconstructions suggest that summer air temperatures cooled in Northern and Western Iceland as sea ice increased with the coldest period occurring during the 18th and 19th centuries

(Ogilvie and Jónsson, 2001; Moros et al., 2006; Massé et al., 2008; Gathorne-Hardy et al., 2009; Axford et al., 2009, 2011; Langdon et al., 2011; Cabedo-Sanz et al., 2016; Holmes et al., 2016). Paleo- and historical records, however, indicate that sea ice was only present along the southern and western coasts of Iceland, where our study site VGHV is located, during severe ice years when sea ice is advected clockwise around the country (Ogilvie, 1996; Axford et al., 2011; Cabedo-Sanz et al., 2016). Similarly, millennial-scale changes in spring temperatures inferred from biogenic silica in western Iceland are decoupled from temperature and sea-ice changes in Northern Iceland, suggesting that spring temperatures are likely more sensitive to changes in regional SSTs (Geirsdóttir et al., 2009). SST reconstructions near southern Iceland show that surface temperatures either increased (Berner et al., 2008; Thornalley et al., 2009; Miettinen et al., 2012; Orme et al., 2018) or did not significantly change (Sicre et al., 2011; Van Nieuwenhove et al., 2018) over the last 2,000 years. Marine reconstructions of temperature from below the summer thermocline and bottom water record a decrease in mean annual temperatures over the Common Era (Thornalley et al., 2009; Ólafsdóttir et al., 2010; Moffa-Sánchez et al., 2014) as the transport of warm North Atlantic Current waters by the Irminger Current decreased over the last 2,000 years (Ólafsdóttir et al., 2010). Based on existing paleo- and historical records we conclude that sea ice feedbacks only play a minor role in driving long-term changes in winter and spring temperatures at our study site, whereas an increase in SSTs along the southern coast could contribute to the warming trend observed in our record. However, discrepancies in existing proxy records makes it difficult to correlate changes in SSTs to changes in winter and spring temperatures at VGHV." (lines 281-301)

Reviewer comment: Finally, as the authors point out in section 2.4, Iceland receives little sunlight during winter: I therefore recommend them to plot early spring insolation in Fig. 6a instead of winter + spring insolation.

Response: We will modify Fig. 6a to plot spring and winter insolation separately.

We modified Fig. 6a to plot spring and winter insolation separately.

Reviewer comment: Section 4.2: the authors (partly) attribute higher-frequency changes to shifts in regional climate dynamics, notably the NAO. When doing so, it would be most helpful to provide a contextual understanding of this complex system on Iceland – what happens to the different components of the regional climate system during (shifts between) positive/ negative NAO phases. Now, it oft feels as if this discussion is shoehorned into an NAO mould using a hotchpotch of sources. Also, respect the sampling and chronological resolution of this dataset: I don‘t think it warrants attribution to multi-annual forcing mechanisms.

Response: Thank you for the suggestion. We will update the text in section 4.2 to discuss forcings that are important on multi-decadal timescales and how they influence the regional climate of Iceland, particularly during the winter and spring season.

As discussed below and as we will explain in the modified text, it is hypothesized that low frequency changes in instrumental and paleoclimate archives from the North Atlantic region are driven by variability in the NAO (e.g. Hurrell, 1995; Pinto & Raible, 2012; Ortega et al., 2015). A recent study demonstrated that NAO variability on interannual to decadal timescales is most likely dominated by meridional shifts in the jet stream and storms tracks, whereas on multi-decadal timescales NAO variability is associated with changes in the speed and strength of the storm tracks (Woolings et al., 2015). On multi-decadal timescales studies have also linked variability in the NAO to changes in sea ice (Delworth et al., 2016), the Atlantic meridional overturning circulation (Delworth et al., 2016), and the Atlantic Multi-decadal Variability (Omrani et al., 2014, 2016; Peings & Magnusdottir, 2014).

We modified the text in section 4.2 as follows:

"The NAO, defined by differences in sea-level pressure between the subpolar low and the subtropical high, is a major source of atmospheric variability during the winter months (Hurrell, 1995). Although the NAO is mainly associated with interannual timescales, there is also evidence that NAO-like patterns can emerge at multi-annual to centennial timescales, potentially linked to coupled changes in oceanic and atmospheric circulation (Visbeck et al., 2003; Delworth et al., 2016; Yeager and Robson 2017). For instance, a positive (negative) NAO phase that persists for multiple winters can lead to increased (decreased) deepwater formation in the Labrador Sea and strengthening (weakening) of the subpolar gyre and the meridional overturning circulation, thereby resulting in an increased (decreased) transport of warm waters towards the poles (Eden and Jung, 2001; Visbeck et al., 2003; Latif et al., 2006). Alternatively, an increase in the southward transport of polar waters could also result in a reduction of deepwater formation in the Labrador Sea and a weaker subpolar gyre, leading to a decrease in northward oceanic heat transport and centennial cooling of ocean and regional air temperatures (Moffa-Sánchez and Hall, 2017; Moreno-Chamarro et al., 2017)." (lines 348-358)

"In contrast, terrestrial records from the Arctic and Northern Europe indicate that temperatures were on average cooler between c. 450-700 CE and c. 500-650 CE, respectively (Kaufman et al., 2009; Sigl et al., 2015; Helama et al., 2017). A peak in sea ice is also recorded in a high-resolution IP_{25} reconstruction from the North Icelandic shelf (Cabedo-Sanz et al., 2016), whereas lower resolution records that were developed using quartz and IP_{25} show a gradual increase in sea ice after c. 400 CE but not distinct peak (Moros et al., 2006; Cabedo-Sanz et al., 2016). Increases in sea ice during this time period are attributed to a southward shift of the subpolar front and the increased advection of drift ice from Greenland to Northern Iceland (Moros et al., 2006; Cabedo-Sanz et al., 2016), leading to cooler winter and spring temperatures in Northern and Southern Iceland." (lines 369-376)

"Summer temperature reconstructions from lakes in Northern and Western Iceland also record warmer temperatures c. 800-1300 CE but with distinct cold excursions occurring between c. 1000-1300 CE (Axford et al., 2009; Gathorne-Hardy et al., 2009; Holmes et al., 2016). Peaks in sea ice, however, are only noted after c. 1200 CE (Ogilvie, 1992; Ogilvie and Jónsson, 2001; Massé et al., 2008; Cabedo-Sanz et al., 2016), suggesting that an alternative mechanism, such as the NAO, may be responsible for the short-term variability observed in terrestrial temperature records from Iceland during this time period." (lines 383-387)

"In the VGHV record, multi-decadal variability and an inconsistent temperature response to major radiative forcings during the LIA suggest that temperature anomalies during the winter and spring are driven by both forced and unforced variability. For instance, the strong negative radiative forcing after the Samalas eruption (1258 CE) and the Wolf solar minimum (c. 1280-1350 CE) correspond to an increase in drift ice along the North Icelandic shelf (Fig.

7; Massé et al., 2008; Cabedo-Sanz et al., 2016), a cold excursion in winter subsurface temperatures from the North Icelandic shelf c. 1350-1500 CE (Harning et al 2019), and cooling in the VGHV temperature record. Similarly, the cumulative effects of the Dalton solar minimum c. 1790-1830 CE and multiple major volcanic eruptions (i.e., Laki 1783 CE, unidentified 1809 CE, and Tambora 1815 CE; Sigl et al., 2015; Toohey and Sigl, 2017) in the late 18th and early 19th century could have resulted in enhanced sea ice feedbacks and cooling in VGHV temperatures between c. 1800-1900 CE (Massé et al., 2008; Zanchettin et al., 2012; Cabedo-Sanz et al., 2016). The inconsistent response in VGHV temperatures to volcanic eruptions and solar minima between c. 1450-1750 CE could be associated with stochastic climate processes, such as the NAO, that counteracted the effects of negative radiative forcings and led to winter warming over Iceland rather than cooling.

On multi-decadal to centennial timescales, changes in the VGHV record do not consistently correspond to major temperature anomalies observed during the summer months. The differences in seasonal climate responses to external forcings imply that the regional manifestation of these events depends on the initial state of the atmosphere and ocean but is also modulated by internal climate variability (Zanchettin et al., 2012; Otto-Bliesner et al., 2016; Anchukaitis et al., 2019).” (lines 409-425)

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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 and edits to the manuscript (highlighted in blue).

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 ($U^K_{37} = 0.029T-0.49$, $r^2 = 0.60$), 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} = 0.030T-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} = 0.0245T-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} = 0.0255T-0.804, r^2 = 0.85, D'Andrea et al., 2012), Toolik Lake in Alaska (U^{K}_{37} = 0.021T-0.68, r^2 = 0.85; Longo et al., 2016), and Vikvatnet in Norway (U^{K}_{37} = 0.0284T-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} = 0.029T (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.

We have modified section 2.3 to discuss previous temperature calibrations and reconstructions using alkenones from lake sediments as follows:

"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; Richter et al., 2019). The Northern Hemisphere lake calibration for Group I alkenones, which includes VGHV, was developed using the average spring temperatures for each lake during ice-off and the main Group I Isochrysidales bloom (U^{K}_{37} = 0.029T-0.49, r^2 = 0.60, RMSE = ± 1.69°C; Longo et al., 2018). An updated calibration for Group I that includes additional lakes in northeastern China (U^{K}_{37} = 0.030T-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} = 0.0245T-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} =

$0.0255T$-0.804, $r^2 = 0.85$, D'Andrea et al., 2012), Toolik Lake in Alaska ($U^K_{37} = 0.021T$-0.68, $r^2 = 0.85$; Longo et al., 2016), and Vikvatnet in Norway ($U^K_{37} = 0.0284T$-0.655, $r^2 = 0.94$; D'Andrea et al., 2016). Temperature calibrations using the U^K_{37} index were successfully applied to develop high resolution records of summer temperatures in Greenland (c. 5,600 yrs BP; D'Andrea et al., 2011) and Svalbard (1,800 yrs BP; D'Andrea et al., 2012) and a winter-spring temperature record in Alaska (16,000 yrs BP; Longo et al., 2020). However, regional variability in the relationship between the U^K_{37} index and temperature requires the development of local temperature calibrations (Wang and Liu, 2013; D'Andrea et al., 2016; Longo et al., 2016). Unfortunately, there is currently no local calibration for Icelandic lakes." (lines 128-141)

In addition, we have modified the discussion to include previous alkenone reconstructions of winter and spring temperatures:

"For instance, pollen records of cold-season temperatures from North America and Europe (Mauri et al., 2015; Marsicek et al., 2018) and an alkenone reconstruction of winter-spring temperatures from Alaska (Longo et al., 2020) suggest that increasing winter and spring orbital insolation over the Holocene drove warming during the winter and spring season." (lines 304-307)

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.

We have added the following sentences to clarify the points discussed above:

"There are no competing effects of summer (JJA) or fall (SON) insolation and air temperature on spring lake water temperatures and the timing of ice-out." (Section 3.2, lines 217-219)

"Lake water temperatures in VGHV solely respond to changes during the winter and spring season because the lake re-freezes every winter and reaches minimum lake water temperatures, meaning any influence from the previous summer or fall season are negligible (e.g. Assel and Robertson, 1995)." (Section 4.1, lines 274-276)

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.

We have added the following sentence to section 2.4 to clarify the purpose of our lake model:

"The purpose of the lake model was to determine the sensitivity of our proxy to different forcing mechanisms by assessing the magnitude of the temperature response and timing of ice-melt relative to our control simulation." (section 2.4, lines 150-152)

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.

We have modified section 2.4 to highlight the points discussed above as follows:

“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. To constrain the seasonality of our proxy, we perturbed the ERA interim seasonal air temperature values by -7 °C, -3 °C, 0 °C, +3 °C, and +7 °C and re-ran the lake model with the adjusted parameters.” (section 2.4, lines 158-161)

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.

We have updated discussion section 4.1 to include the following sentence:

“However, as our record only spans the last 2,000 years, the warming trend in our record could also be a feature of the last millennium associated with regional processes.” (lines 279-280)

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.

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