Response to the reviewers' comments

We thank the two reviewers and editor Denis-Didier Rousseau for their constructive and detailed comments to our manuscript. In the following we will respond to all concerns raised, first answering the main point of criticism, and then in a point-by-point reply.

Detailed response (qualitative NAO polarity changes in TOC from KKJ sediments):

We agree with Referee #1 about the non-stationary behavior of changes in the North Atlantic Oscillation (NAO) and the problems of covering these changes in individual records. To respond to the Referee's comments and perform the requested further examinations, we now compare our TOC record from KKJ sediments with 5 different NAO reconstructions, updated the connected Fig. 12 and added new paragraphs to chapter 5.3.2., discussing the broad covariance and remaining disagreements between the KKJ TOC and NAO records, as well as the possible underlying mechanisms (see the revised chapter and Fig. 12 below). However, despite the resulting visible matches, the correlation coefficients between the KKJ TOC record and NAO reconstructions >1000 years (all sampled to 20-year resolution) are low between 0.14 and 0.32 with significance levels between 0.05 and 0.2. Most likely and important reason are the uncertainties of in particular the individual radiocarbon-based chronologies, allowing to allocate shorter-term variability and hampering the statistical 1 to 1 matching of these changes. For example, the average chronological uncertainty of the investigated KKJ sediment record is ±79 years. Considering this technical limitation, we think that correlation coefficients and significance levels do not reflect a realistic degree of similarity between the records and prefer not to show them.

The revised chapter (red text is new):

5.3.2. Decadal to centennial productivity variability and NAO

Today, meteorology at KKJ is correlated with the predominant mode of the NAO (Fig. 11). The NAO is the major source of atmospheric circulation variability over the North Atlantic and Europe, primarily during winter (Hurrell, 1995). During its positive phase Scandinavian winter climate is characterized by above average temperatures, precipitation and windiness (Fig. 11) (Hurrell, 1995).

To investigate the preservation of decadal to centennial NAO polarity changes in KKJ sediments, we compare the TOC productivity record during SDU 3 and 4 with reconstructions of the NAO from tree rings and speleothems for the Little Ice Age/Medieval Warm Period transition (Trouet et al., 2009; Wassenburg et al., 2013), speleothems from Scotland covering the last 3000 years (Baker et al., 2015), Greenland lake sediments back to 5200 a BP (Olsen et al., 2012) and marine sediments from off Norway back to 7800 a BP (Becker et al., 2020) (Fig. 12).

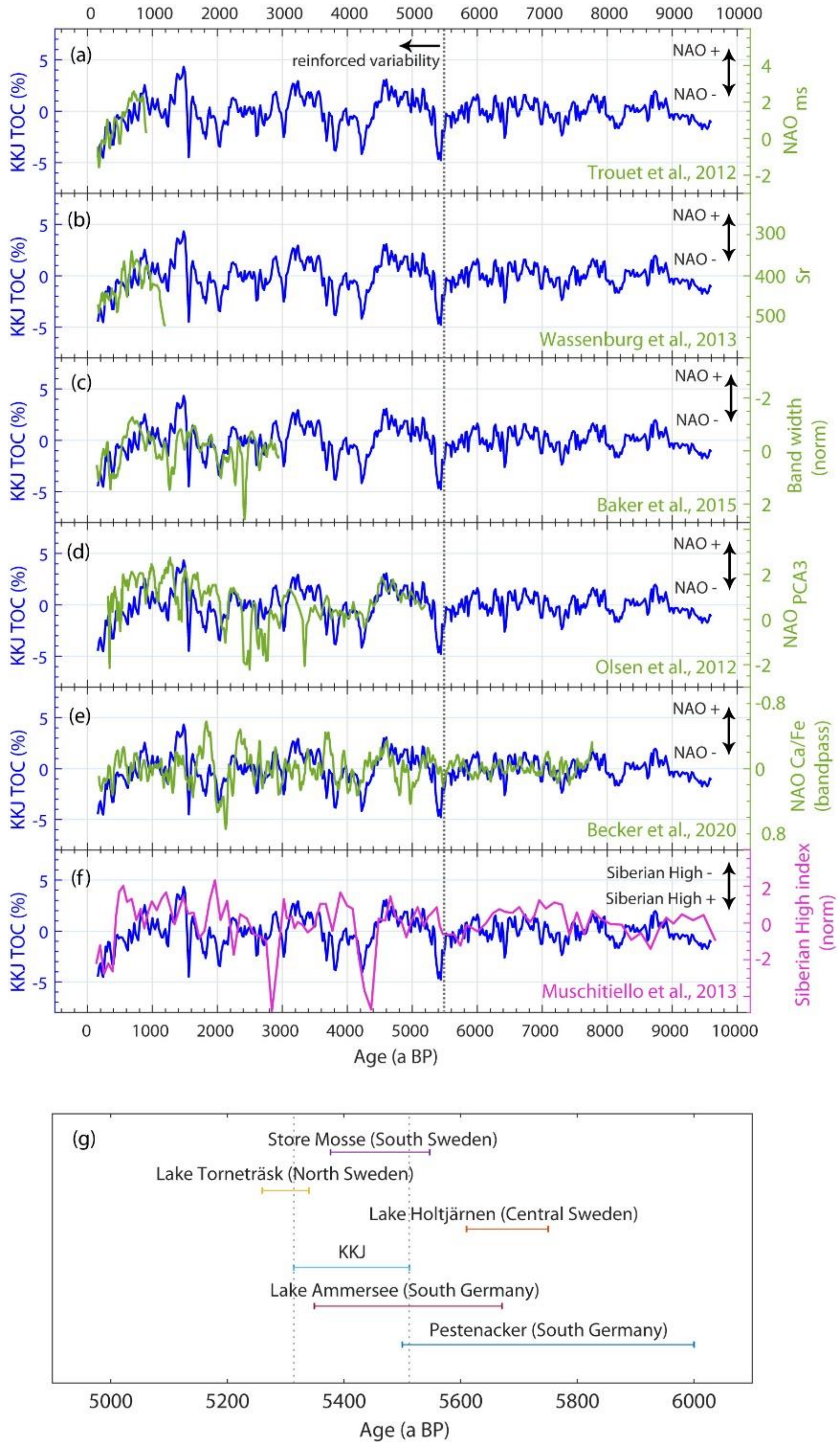
In particular, the NAO reconstructions by Olsen et al. (2012), Trouet et al. (2012), Wassenburg et al. (2013) and Baker et al. (2015) resemble most of the multi-decadal to centennial features in the TOC record from KKJ sediments (Fig.12). Productivity in the lake tends to be higher, when the NAO is in a more positive mode (Fig. 12). The three latter NAO reconstructions also co-vary with the KKJ TOC record during the last ~1200 years, when the fit with the Olsen et al. (2012) NAO reconstruction is low. A possible reason for the differences between the KKJ TOC record and Olsen et al. (2012) NAO reconstruction during this period might the non-stationary behavior of this atmospheric seesaw that is difficult to capture in individual archives, as well as its interplay with other modes of oceanic and atmospheric variability, like e.g. the East Atlantic West Russia oscillation (Jung et al., 2003; Krichak and Alpert, 2005). Comparing our KKJ TOC record with the multi-millennial NAO reconstruction by Becker et al. (2020) reveals covariance for most of the time, but also some inconsistencies around 1800, 2400 and 3700 a BP (Fig. 12). These inconsistencies might result from the proposed further influences of changes in the subpolar gyre and Atlantic Multidecadal Oscillation on this marine NAO reconstruction (Becker et al., 2020).

Few sporadic negative peaks in the NAO records from Greenland lake sediments and Scottish speleothems that are not reflected in the TOC record from KKJ sediments might be explained by local climate or archive-specific noise (Fig. 12). Temporal inconsistencies of a few decades between the KKJ productivity record and NAO reconstructions are likely associated with the chronological uncertainties of, in particular, the ^{14}C-dated sediment archives (Fig. 12). For example, the average chronological uncertainty for the investigated KKJ sediment core is ±79 years.

Based on this comparison, we interpret our decadal to centennial TOC record from KKJ sediments during the complete 9612 (+255/-144) years to mainly reflect qualitative changes in NAO-like atmospheric circulation. Analogue to the multi-millennial trend, main mechanistic linkage for the observed decadal to centennial TOC variability in KKJ might be the influences of the NAO polarity on winter temperature, ice cover duration and lake productivity.

This interpretation is supported by meteorological studies and monitoring results from several Swedish lakes indicating a significant influence of the NAO on annual to seasonal temperatures, ice cover duration and, consequently, productivity (Blenckner et al., 2004; Chen and Hellström, 1999; Karlsson et al., 2005). Winter temperatures in Sweden are warmer, ice cover is shortened and productivity higher, when the NAO is in a positive mode (Blenckner et al., 2004; Chen and Hellström, 1999; Hurrell, 1995). The importance of the NAO for ice cover duration can be exemplarily described by monitoring results from three lakes in vicinity to KKJ (all 60°N in Sweden) covering the period AD 1961 to 2002 (Blenckner et al., 2004). Mean ice cover duration of the three lakes within this time-interval varies between 99 and 203 days and the NAO is one significant driver of the up to >3 months changes in ice cover duration (Blenckner et al., 2004; Ptak et al., 2019). In addition, NAO influences on ice cover duration of Swedish lakes are particularly strong south of 62°N where KKJ is located since the blocking of the North Atlantic zonal atmospheric circulation by the Scandinavian Mountains is minor (Blenckner et al., 2004).

Further influences of changes in Siberian High (SH) strength on productivity in KKJ are possible, since the lake is situated at the western boundary of this atmospheric system. However, on the one hand, meteorological investigations and paleoclimate reconstructions indicate that NAO and Siberian High changes are interdependent, particularly on long time-scales (Fig. 12). Siberian High strength tends to be reduced when the NAO is in a more positive mode (Chen et al., 2010; He et al., 2017). On the other hand, KKJ is located in direct vicinity to the North Atlantic within the path of the westerly storm tracks. Therefore, considering the location of KKJ and intercontinental teleconnections, we prefer to relate the decadal to centennial changes in TOC as driven by NAO-like changes in atmospheric circulation.



Revised Fig 12. The revised figure now includes a comparison of the KKJ TOC record with 5 different NAO reconstructions and an index of Siberian High strength (a-f). In (g) we added the onset of reinforced paleoclimate variability at ~5450 a BP recorded in the nearby Store Mosse bog. We will

add the archive-type (e.g. tree rings) and geographical position of the compared NAO records to the figure caption.

Point by point response to Referee #1

This is a very interesting study which attempts to provide insights into the North Atlantic Oscillation (NAO) variability throughout most of the Holocene. The detailed sedimentology from lake Kalksjon, west-central Sweden, is excellent and provides some justification for its use as a qualitative reconstruction of the NAO. Overall, I found the manuscript well written and will be of high interest for the paleoclimate community studying the climate during the Holocene for this region. It is therefore suitable for Climate of the Past. However, to assess this archive as a reconstructed “qualitative” record of the NAO, I believe there needs to be further examinations.

Thank you!

Major comments:

Different NAO reconstructions show periods of coherency and often no coherency at all. This is partly because the NAO itself exhibits non-stationary behavior, so the use of one single location may not capture the whole variability. One aspect that may have been overlooked in this paper is the other existing NAO proxies. Have you explored other records that may be sensitive to large-scale and long-term NAO fluctuations? That said, from 1800BP to the present, the NAO from Olsen et al. (2012) and the TOC record don’t seem to match quite well, but perhaps if you plot different reconstructed NAO, a better co-variability (correlation) may be seen. I am thinking of speleothems in Europe and North Africa as well as the new one from Becker et al. (2020). See also Wassenburg et al. 2016 Nat Geosci, Baker et al. 2015, etc.

Please see our Detailed Response.

Figure 12 shows the relationship between paleo NAO (Olsen et al. 2012) and the TOC content in the studied lake. When sampling both records to the lowest resolution of the corresponding record; do you find any significant correlations? Same comment for the Siberian High.

Please see our Detailed Response.

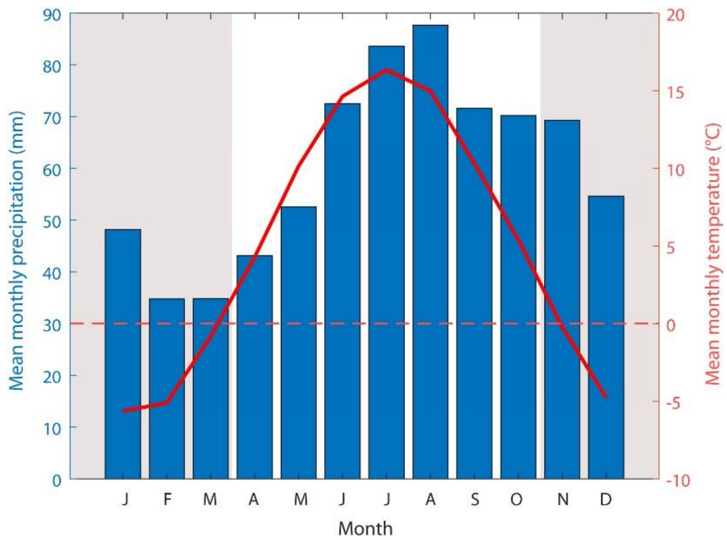
Also, the lack of coherence between your record and other NAO proxies could be explained by other mode of variability that may have been more persistent in the past. The Scandinavian Blocking, for example, accounts for ~27% of the winter North Atlantic variability. A persistent Scandinavian Blocking in winter would translate to cooler conditions in the region, thereby presumably increased ice cover time (in turn less productivity). Any thoughts on this? I suggest to add more discussion around line 345.

Please see our Detailed Response.

Some other minor comments:

Figure 3: Given you are dealing with decadal to centennial scale variability, I think an average (monthly?) of temperature and precipitation would improve visualization.

We revised Fig. 3 following the referee's suggestions:



Revised Fig. 3 now showing monthly averaged precipitation and temperature data from the meteorological station Torsby (~5 km west of Lake Kälksjön) for the observation period.

Figure 4 shows the composite with the XRF cluster stratigraphy. It should be located after figure 7 (PCA of the elements).

We agree with Referee #1 that the XRF cluster stratigraphy in Fig. 4 should be in theory located after Fig. 7. However, without the direct comparison with the $\delta^{13}C$, TOC, C/N, S/Ti and Ti proxies from KKJ sediments a lot of information about the cluster stratigraphy and the connected sedimentology would get lost. Therefore, we would like to keep the cluster stratigraphy in Fig. 4. To account for the reviewer's comment, we added to the text '(see Fig. 4)', when the XRF cluster stratigraphy is mentioned.

Additionally, we slightly modified the caption of Fig. 7 into:

Figure 7: Statistical analyses of the XRF profiles from Lake Kälksjön (KKJ) sediments. (a) Covariance biplot visualizing the correlations of the main elements with regard to the first two principal components. (b) Hierarchical clustering solution reflecting the difference between the detrital sediments of SDU 1, 2, and 5 and organic sediments of SDU 3, 4, and 6.

Figure 4: Add average temporal resolution for each cluster, i.e., mm/year

To improve/keep the readability of Fig. 4, we added the requested information to section 5.1. (Holocene evolution of Lake Kälksjön). Only the names of the SDU remained as text in the figure. Please see also the related comment to Referee #2, requesting SDU age ranges in Fig. 4.

Figure 10: the sharp decline in TOC falls within 4.2k BP. Do you consider that your proxy responded to the 4.2k event?

Considering the complete TOC record from KKJ sediments shown in Fig. 12, the drop in TOC at 4.2 ka is not unique and appears somewhat short for marking the coinciding climate event. Therefore, we would like to avoid a discussion about the connection of this peak to the 4.2 ka climate event.

Figure 12: we don’t see much the Trouet et al. NAO, the color is too pale. Also, why not the selection of the Ortega et al. reconstructed NAO?

Please see our Detailed Response and the revised Fig. 12. We omitted the NAO reconstruction by Ortega et al. (2015) for the last millennium since it does not reflect the shift from a more negative to more positive NAO polarity between the Little Ice Age and Medieval Warm Period that is the most distinctive last millennium feature in the other 5 NAO reconstructions used in this study.

Figure 12: the lines of the SH index are outside the x-axis.

We corrected that.

Figure 13: the spectral peaks don’t seem to match quite well, perhaps a cross-spectral analysis would give something better. I would suggest moving this to the supplement.

Considering the non-stationarity of the NAO suggested by the Referee, we prefer not to show spectral analyses or cross wavelet analyses in the updated manuscript.

Line 89: could you provide more information as to how the grain-size was extracted?

The particles-sizes of individual detrital grains were measured with a scale under the microscope. We added ‘microscopic’ to the text.

Section 3.3: provide information on how many thin-sections were produced.

We added to the text that 80 thin-sections were produced from KKJ sediments.

Section 3.5: Why no pollen analysis on other SDU?

Pollen analysis were performed on KKJ sediments to cover the transition between SDU 3 and 4 (transition to higher amplitudes in the TOC record) and the recent period of most distinct human activity. For the remaining periods without exceptional variability in KKJ TOC record, we believe that it is appropriate to refer to pollen results from nearby lakes to rule out major human influences.

Section 4.3: Add a Table showing the matrix correlation between µ-XRF data

We added the following table with a correlation matrix for the XRF data from KKJ sediments to the manuscript:

New Table. Correlation matrix for the XRF profiles from the Lake Kälksjön KKJ19 composite profile.

	Al	**Si**	**S**	**K**	**Ca**	**Ti**	**Mn**	**Fe**
Al	1	0.95	-0.92	0.81	0.75	0.87	-0.37	-0.83
Si		1	-0.92	0.90	0.71	0.90	-0.28	-0.92
S			1	-0.88	-0.70	-0.91	0.14	0.77
K				1	0.45	0.91	-0.04	-0.83
Ca					1	0.61	-0.46	-0.68
Ti						1	-0.35	-0.82
Mn							1	0.25
Fe								1

Line 104: 3s is deem low. Is this a typo?

3 seconds is correct. Using the latest XRF detector in combination with high electric current (60 mA) allows measuring with such low acquisition time.

Line 105: why only these elements? For example, why is Ca omitted?

The elements mentioned in line 105 are selected based on the amount of zero-values and replicate measurements. This is now explained in lines 102-107.

Line 106: How did you build the µ-XRF composite? Elements often decrease (increase) their values at both edge of the sediment sections. Did you remove those data?

The XRF data were measured for composite profile KKJ19 omitting sediment core endings. We added to the text that the XRF data were acquired for composite profile KKJ19.

Line 239: There is no Ca profile showing these peaks. Maybe add into supplement.

Instead of adding an additional figure with Ca, we now refer to the microscopically visible liming layers at 3.5 and 5 cm composite depth. A micrograph of one of these layers is shown in Fig. 4.

Line 364-365: Please rephrase

The rephrased sentence:

Decadal to centennial productivity changes revealed by the KKJ sediment record indicate a shift towards reinforced variability concurrent with the onset of Neoglaciation ~5450 cal. a BP (Fig. 12).

Thank you very much!

Point by point response to Referee #2

I agree with reviewer 1 that this is a very interesting and well-written paper that provides new insight into NOA variability using a Swedish lake record. I am, however, not an expert in NAO and NAO variability so I have focused my review on other aspects of the paper.

Thank you!

Comments:

Line 18   Maybe a minor comment, but I think that LKJ would be a better acronym than KKJ

We prefer to continue using KKJ as acronym for Lake Källksjön. The works on this sediment archive in different laboratories since the coring in 2019 were performed using KKJ. A changed acronym might cause confusion during future work on this sediment archive.

Line 19 I prefer CE (Common Era) rather than AD

We replaced AD with CE in the text and figures.

Line 42 Here it might be useful if you define what you mean with the western Baltic region (or the western Baltic Sea region?). There are at least ten different definition of the "Baltic Region" in Wikipedia

We now define in line 35 that our 'Western Baltic region' comprises 'south-central Scandinavia'.

Line 55 I checked the Swedish Land Survey online maps and long. 13°03'E is more correct.

Thank you. We changed this information accordingly.

Line 59 west

Corrected.

Line 63 Figure 3 shows daily temperatures and precipitations, not mean monthly temperatures, see also comment by Rev. 1

The revised Fig. 3 now shows mean monthly temperature and precipitation values for the observation period at the SMHI station Torsby. Please see the revised figure in our response to Referee #1.

Line 105 I agree with Rev. 1, why was not e.g. Zr and Ca analysed.

As stated before, the elements mentioned in line 105 are selected based on the amount of zero-values and replicate measurements. This is now explained in lines 102-107.

Line 228 I would use "concentrations of the artificial radionuclides" rather than "contents"

We replaced ‘contents’ with ‘concentrations’.

Line 238 See comment by Rev. 1. Was Ca measured after all?

Please see the comment above. Yes, Ca was measured. A positive correlation with the elements Ti and K indicates its predominantly detrital origin.

Line 266 I was slightly confused by the discussion about the isolation of the lake basin from Ancient Lake Vänern. I have not read the Risberg et al paper in any detail, but the uplift history of the area is complicated with evidence of irregular postglacial isostatic uplift. Hence, the comment that the isolation of L. Skjutsbolstjärnet located at a similar location (and what is meant by that?) and height supports your isolation point must be clarified (or deleted?). The isolation age of L. Skjutsbolstjärnet is c. 9600 uncalibrated C14 years which calibrates to c. 10,900 cal a BP

Based on the comment of Referee #2 on the irregular uplift history of the region around KKJ, we deleted the information about the isolation age of Lake Skjultsbolstjärnet.

Line 269 cal is missing before “a BP” (Stanton et al. 2010)

We added cal.

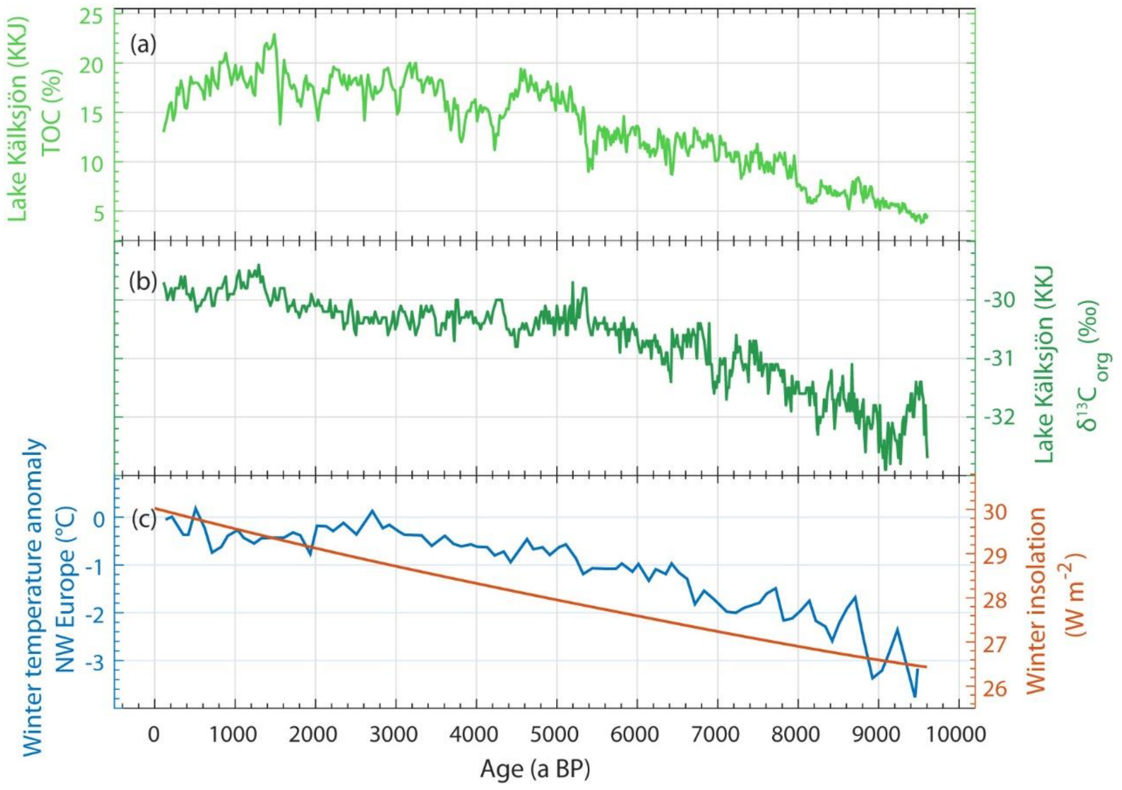
Line 313 typo? Should be east of L. Kälksjön

We corrected the typo.

Line 318 My alternative interpretation of the TOC contents would be “a sharp increase until ca 4500 cal a BP with a drop at ca. 5300 cal a BP”, i.e. the increase continues another 1000 years, followed by more stable values until recent times. I would also add $\delta^{13}C$ to Figure 10.

As suggested by Referee #2, the revised Fig. 10 now also shows $^{13}C_{org}$ along with TOC from KKJ sediments. Comparing both records from KKJ sediments indicates the difficulties of identifying a certain change-point in its multi-millennial behavior. Therefore, we slightly modified the connected sentence to:

The multi-millennial upward trend in TOC contents (and simultaneously increasing $\delta^{13}C_{org}$ values) interpreted to reflect progressively increasing productivity in KKJ reveals a sharper increase until the Mid-Holocene, followed by a more moderate rise until recent times.



Revised Fig. 10 now also showing $^{13}C_{org}$ from KKJ sediments.

Line 331 Does this refer to winter or annual temperatures, precipitation and windiness?

We added 'winter' to the related sentence.

Line 341 I am not certain that the reference to Almquist-Jacobson is 100% correct here. Almquist-Jacobson's sites are situated in an area that may have been settled by humans later than the river and lake valleys in Värmland. There are archaeological findings north and north-west of Torsby dating back to the early Neolithic (3800-3300 BC)

The thank the referee about the information on early Neolithic findings north and north-west of Torsby. However, we did not find coincidences between changes in the TOC record and changes in pollen indicators of human activity directly from KKJ sediments during this early Neolithic period.

We replaced the reference to Almquist-Jacobsen with the one by Eddudottir et al. (2021) finding an increase in human activity at about the same time (2100 a BP) in the much more nearby Lake Karebolssjön (~25 km northeast of KKJ). Still, there is no corresponding change in the TOC record from KKJ sediments.

Line 364-374 Here you should also discuss proxy records from Sweden showing climate shifts at this time, e.g. the peat record from Store Mosse (Kylander et al., 2013; QSR) and lake level records from L. Bysjön (Digerfeldt, 1988; Boreas). These could also be shown to Fig. 12.

We agree with Referee #2 about the importance of adding results from the regional paleoclimate records of the Store Mosse bog and Lake Bysjön to our discussion on reinforced NAO-like atmospheric variability since ~5450 a BP. Supporting our interpretation, the PC4 dust time-series from the nearby Store Mosse bog reflecting wind changes depicts enhanced variability since this time. We added this information to the revised Fig. 12 and the text. Enhanced shorter-term variability since about 5450 a BP is also present in the lake level curve from Bysjön. However, the low resolution of the record inhibits detecting a certain change-point and possible high-amplitude variations. Therefore, we mention the result of shorter-term lake level variability since about 5450 a BP only in the text.

Line 546 Change Väners to Vänern

Done.

Table 1 If possible, give weights and type of material (e.g. terrestrial or lacustrine plant remains?)

We added to Table 1 that all ^{14}C dated material is terrestrial. The weights of the samples are unknown. But, BETA rejects samples before the ^{14}C measurement, if they are too small.

Figure 2 Give the source of the historic document. Museum, library?

We added to the caption of Figure 2 that the document was provided by a local historian.

Figure 4 Sediment deposition units. Give the age range for each SDU, if possible, not only the onset

Please see also our comment on Fig. 4 above. To improve/keep the readability of Fig. 4, we added all requested information to section 5.1. (Holocene evolution of Lake Källsjön). Only the names of the SDU remained as text in the figure.

Thank you very much!