Comments by reviewer #3

We thank reviewer #3 for their constructive remarks, which will improve the manuscript. Our response to the individual comments including potential changes to the manuscript are given below.

This is a very interesting paper that uses unique geologic samples – a cryogenic cave minerals – that grew in a northeast cave of Greenland to reconstruct past climate history. The primary geochemical analyses are mineralogical inspection, stable isotope analyses, and U-Th dating. From these analyses (primarily from the dating results) they deduce that CCMs formed during the Little Ice Age during a period of anomalously high temperatures that occurred over a few days in the summer of 1889 CE. These extreme warm conditions led to widespread melting over the Greenland Ice Sheet.

I am particularly intrigued by the interpretation of "a few days," specifically at LINES 23-24: "We relate the CCM formation to a combination of black carbon deposition and anomalously high temperatures, which occurred over a few days, in the summer of 1889 CE." The time constraint of "days" is an extraordinarily statement – the fact that a few days of extremely high temperatures caused widespread melting over northeast Greenland is an important finding, if it's true. However, I find the author's reasoning for relating CCM growth to this extreme climate event (a few days of warming) insufficient. There is not a thorough explanation for why authors jump to "days"? In the paper, the only citation is Neff et al. (2014). The authors need to add more explanation to this interpretation.

Please see lines 334-339: The timeframe of the event ("a few days") is not deduced by dating of the Cove Cave CCMs, it stems from several publications that all describe wide-spread melting conditions on the Greenland ice sheet (Clausen et al., 1988; Fischer et al., 1998; Keegan et al., 2014; Neff et al., 2014). The unusual conditions of the summer melt episode of 1889 CE therefore provide the most likely explanation as to why it was possible for CCMs to form during a period of cold climate conditions, while the work of, e.g., Neff et al. (2014) provides constraints ("days"). We will rephrase lines 334-337 to make this point clearer.

Overall, though, I find this an intriguing paper and I think the authors did a nice job thoroughly explaining their scientific methods and results. I do have a few clarifying points, though, that I think would make the paper stronger. Also, I feel some sections need added details. Most importantly, I find the authors reporting and explanation of the stable isotope data lacking. I explain this more below:

1. *Does the paper present novel concepts, ideas, tools, or data?* – Yes, the dating of CCC material is exceptionally novel, not to mention the location of this cave as the highest-latitude site with paleoclimate data is intriguing

2. *Are the scientific methods and assumptions valid and clearly outlined?* Yes, I think the authors do a nice job clearly stating their scientific processes and methods.

3. Are the results sufficient to support the interpretations and conclusions? Yes.

4. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes.

5. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes.

6. Does the title clearly reflect the contents of the paper? Yes.

7. Does the abstract provide a concise and complete summary? Yes, except I recommend removing one part, given it is not relevant to main conclusions.

8. Is the overall presentation well structured and clear? Mostly yes, though some sections need more explanation (see my line-by-line comments).

9. Is the language fluent and precise? Yes.

10. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes.

11. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? No.

12. Are the number and quality of references appropriate? Yes, except more should be added in reference to the “few days” warm period in 1889 CE.

Please see our response above.

13. Is the amount and quality of supplementary material appropriate? Yes.

Line-by-line comments

Abstract: I am not sure why authors include the information about CCC_{fine} $\delta^{18}O$ values in the abstract? It is my understanding that they do not use this data to make any interpretations?

Although we use the stable isotope data to identify which type of CCMs we are dealing with and try to compare our data to those of existing studies, we realise that this information does not have to be included in the abstract. We will remove it.

Line 39: Though the authors link CCC formation as a “useful proxy for paleo-permafrost,” they do not state clearly whether the formation of CCC=permafrost is present? It may be worth stating this explicitly for readers who are unfamiliar with CCC.

We already state in line 32 that the existence of CCCs indicates past permafrost presence. We will add to the sentence in line 39 that CCC_{coarse} can be used for the reconstruction of past permafrost (i.e., CCC_{coarse} = palaeo-permafrost) as well as negative cave temperatures close to 0°C.

Line 40: Please state the size difference between CCC_{coarse} and CCC_{fine}. Are CCC samples separated into "coarse" and "fine" categories by eye? By measurement?

They are most commonly differentiated by grain size (~1 mm) but also by their stable isotopic composition, which is the result of the formation mechanism (open vs. closed system). In reality, they seem to occupy a spectrum rather than distinct classes, which is part of an ongoing debate. We will add a statement on the differentiating criteria to the manuscript.

Line 45: Is there a reason the authors report the CCM subtypes as CCC_{coarse} and CCC_{fine} versus CCM_{coarse} and CCM_{fine}? Lines 37-45 explain the difference between CCC and CCM, but then authors refer their CCM samples as CCC? Please clarify, because right now it seems these two are equivalent.

Unfortunately, the nomenclature in previously published studies is slightly confusing. The term "cryogenic cave minerals" (CCMs) encompasses all kinds of cryogenically formed minerals in caves. These minerals are often carbonates, or more commonly calcite, and therefore abbreviated as CCCs (cryogenic cave carbonates), which themselves can be divided into the subtypes CCC_{fine} and CCC_{coarse} based on their mechanism of formation. We must introduce these terms in the paper to be able to compare our results with existing data from the literature, which mostly focusses on CCCs.

Aside from carbonates, CCMs can be composed of other minerals – our samples, of the fine-grained type, are made up of carbonates as well as sulphates. When referring to the carbonate fraction of our samples we use the term CCC_{fine} to differentiate them from the sulphate fraction. We realise, however, that this is confusing to the reader, and we plan to simplify it throughout the paper by dropping the term CCC_{fine} when referring to our samples. We will use the expression "carbonate and sulphate fraction" instead.

Line 48: "*recently called into question*." How? Please briefly state this. Perhaps move line 50 up to follow this sentence, since I believe it's because of detrital thorium contamination?

The accuracy of the $^{230}Th/U$ dating technique using standard evaluation procedures has been recently called into question by showing that the conventionally used correction factors for detrital Th contamination are not universally applicable to CCC_{coarse} samples. We will add this to the manuscript. The dating difficulties mentioned in line 50 refer to CCC_{fine}.

In Figure 2, it is interesting you only find fine-grained CCMs in the red shaded region, yet there are other below-0°C regions. Is there a hypothesis for why CCCs formed only in this location in the cave and not in others? This information may be helpful to scientists who want to go and try and find CCMs in other cave systems.

The conditions under which the Cove Cave CCMs formed are highly unusual (i.e., due to an extreme event under otherwise unfavourable conditions for formation, e.g., too cold and dry). Because the CCMs formed as a result of an extreme event, with contributing factors such as a tectonic fracture in the roof of the cave and an ice cap in close vicinity, the actual cave air temperatures most likely played only a minor or even no role in CCM formation. The location of the CCM accumulation within the cave is probably the result of the location *of the fracture, i.e., where water was able to enter the cave, as well as simple settling (and the lack of flowing water) when the ice sublimated and the CCMs accumulated on the floor of the cave.*

Figure 4: It is difficult to discern the difference between the light vs. darker gray shading colors. A suggestion to make one of the categories black?

Will do.

Line 125: Please specify where common speleothems were collected. Was it the same cave? Right now it is just reported as "in the study area," which is not enough information. This could help shed light on the $\delta^{18}O$ difference between common speleothem and CCCs?

The common speleothems were collected in several caves within the study area (a few square km) including Cove Cave. We will add that to the section. This bigger dataset (using isotopic data from the study area) is used to allow for comparison against existing data, i.e., in Fig. 4. In line 278, where we compare $\delta^{18}O$ of common speleothems and of our CCMs, we clearly state that they are both from Cove Cave.

Section 5.2: Are authors interpreting the low $\delta^{18}O$ values as reflecting contribution of precipitation from the Arctic air mass? Doesn't this location primarily receive precipitation from the Arctic air mass? Why is this significant? Also, the Greenland common speleothems have a higher $\delta^{18}O$ value than CCM $\delta^{18}O$, but they were collected from the same cave? If they are from the same "northeast Greenland" cave, then they should receive precipitation from the same source, and therefore should have the same $\delta^{18}O$? I see at Lines 278-281 the authors address this difference, but do not provide a reason why? Please explain? Even if the authors are not sure why this is, that should be stated. As of now, it is unclear what the assumption of this is, and I find the discussion of the stable isotope data not sufficient.

We are interpreting the low $\delta^{18}O$ values, which can be observed in both our CCMs as well as the Canadian CCC_{fine}, to be the result of the high-latitudinal settings that both sampling areas are located in. We will change this paragraph, focussing more on this latitudinal shift that can be seen in the cryogenic minerals as well as common speleothems, bearing in mind that it would be beyond the scope of this paper to draw major conclusions from this.

Regarding the $\delta^{18}O$ values of CCMs and common speleothems from the same cave, the reviewer is correct, they should show the same values if they were of roughly the same age. Our data is not sufficient to draw definite conclusions, however, we hypothesise that the isotopic composition of the source water has changed: while the CCMs were deposited recently, the common speleothems from the same cave were deposited during an earlier period within the Quaternary under different climatic boundary conditions compared to today. We will not yet disclose the age of the common speleothem samples as those results are intended for another publication and not of relevance here.

We will change the whole section so that both points come across more clearly. We also plan to add arrows to Fig. 4 to represent the mentioned latitudinal shift.

Section 5.2 (continued): What is significant about the Greenland CCMs $\delta^{18}O$ overlap with mid-latitude caves? This is not discussed, and I'm a bit confused why this is significant.

Existing CCC data are strongly biased towards central European/mid-latitude sites. Based on this, the isotopic compositions of CCC_{fine} and CCC_{coarse} are often portrayed to be plotting in distinct O and C isotope ranges. Presenting our data as well as that of Canadian CCC_{fine} indicates that such borders are not universally applicable, especially at higher latitudes. Exploring this further is beyond the scope of this manuscript. We will add a short statement to section 5.2 to improve clarity.