Submission of reply to the comments made by Reviewer #2
Ms. Ref. No.: CP-2020-107
Title: Cryogenic cave carbonates in the Dolomites (Northern Italy): insights into Younger Dryas cooling and seasonal precipitation

Reviewer #2

We thank the reviewer for his/her critical comments. We address below the points raised by this referee (in italics) and try to clarify what we are doing in response to these comments (blue).

Sincerely,

On behalf of all the co-authors,
Gabriella Koltai

Main comments

Koltai et al. use a combination of cave air temperature modeling and U/Th dating of cryogenic cave carbonates (CCC) to discuss climate variability during the YD in the SE Alps (Dolomites). The topic is becoming a hotly debated one, as more and more studies suggest that climate during the YD was spatially, temporally and seasonally different throughout Europe and the author's paper comes to add more information to this debate. While bot the title and discussion are tantalizing, I fond that the authors overstretch themselves in analyzing to many climate variables over a long period of time based on a limited data set (several U/Th dates) buttressed by modeling. Several points should be made clear before publication of the paper. I detail these in a few general and technical comments below.

The description of our approach may have been unclear and we are thankful for pointing this out. This paper utilizes a novel paleoclimate archive (cryogenic cave carbonates, or CCCs for short) that allows to precisely constrain permafrost thawing events in the past, when the cave air temperature was very close to the freezing point (e.g. Zak et al., 2018 and references therein, for further discussion on CCC formation see lines 76-85 and 225-266).

In our study we use a 1-d heat conduction model developed by one of the co-authors to investigate how the atmospheric climate signal is transferred into the subsurface. The different scenarios are based on regional proxy data reconstructions for the Allerød (Ilyashuk et al., 2009a) and the YD (e.g. Affolter et al., 2019; Frauenfelder et al., 2001; Ghadiri et al., 2018; Luetscher et al., 2015). These studies suggest an approximately 3 to 10°C decrease in mean annual air temperature (MAAT) during the YD compared to modern day. Our experiments take advantage of these studies and investigate under which climate conditions CCCs could have formed at our study site.
The heat-flow model simulates the penetration of the ambient seasonal temperature signal to 50 m depth. We use local meteorological data to characterize modern day conditions (see Table 2) and palaeotemperature estimates from the Majola Pass (Ilyashuk et al., 2009b) to define the input parameters for scenario 1 (Allerød interstadial climate). As a recent study by Schenk et al. (2018) suggested that YD summers remained relatively warm with temperature decreases of 4.3°C in NW Europe and 0.3°C in E Europe relative to the preceding Bølling interstadial, we kept the July temperatures 3-4°C lower modern values (Table 2) and attributed most of the MAAT change to

winter cooling. We use the output of this simulation as the starting condition for all early YD experiments. As a second step, we model the penetration of the seasonal signal without the presence of winter snow to provide an endmember for the YD cooling (scenarios 2a, 2b, 2d). The results show that the subsurface would be overcooled and prevent CCC formation latest 100 years after the start of the cooling. Then as a next step we include the buffering effect of a winter snowpack insulating the ground from the winter chill. This buffering effect (snow ΔT) is set to its maximum in scenarios 2c and 2e to test if a similar amplitude of cooling investigated in scenarios 2b and 2d (Table 2) would allow CCC formation given the presence of a winter snow cover. As discussed in the manuscript (lines 304-306) studies in modern permafrost areas suggest that even a 35 cm thick stable winter snow cover may result in a 5.5°C increase in mean ground surface temperatures (Zhang, 2005 and references therein). Therefore, our snow ΔT values of 5°C and 4.7°C are considered to be realistic for the YD at this alpine setting. With these two input parameters we characterize the maximum possible amplitude of winter cooling in the absence or presence of a winter snow cover.

Several papers discussed climatic inferences based on the U/Th age of CCCs and a wide range growth periods have been found leading to several possible climatic conditions leading to the precipitation of CCC (Zak et al., 2004, 2009, 2012, Luetscher et al., 2013, Spoetl and Cheng, 2014 – quite a few of these are missing from the cited literature section. . .). These authors have found CCS growing during warm and cold, dry and wet periods during MIS6, MIS4, MIS3, MIS 2, mid-to-late Holocene (Roman and Medieval Warm Periods). From these studies, it occurs that a wide range of external climatic conditions are possibly favourable for the formation of CCCs in caves and it is the peculiarities of cave climate that are in the end responsible for this. Consequently, I find the climatic inferences made in this paper somehow only poorly supported by the data but strongly relying on the thermal modeling. While the data are what they are, the modeling methods and results should be explained in more detail and the various assumptions (e.g., lack or presence of permafrost, assumed temperatures, buffering effect of snow cover etc) in choosing input data and favouring one model over the other better explained.

We agree with the reviewer that the local cave microclimate may influence CCC formation to a considerable extent in complex cave systems (cf. also Koltai et al., 2020), however we are confident that this was not the case during the YD in Ciocccheroch Cave. In the manuscript (lines 96-101) we present the temperature data of a 1-year monitoring of the CCC-bearing cave chamber and provide a discussion the microclimate of the site (lines 238-253).

Regarding the modeling methods, we refer to our previous comment from Reviewer#2 (. We would like to emphasize that all previous studies interpreted CCCs as proxies for paleo-permafrost thawing. In our paper we go a step further and apply a 1-d heat flow model to characterize under which climate conditions CCCs could have formed in the cave. We emphasize in the manuscript that CCCs form under a stable cave microclimate when the cave air temperature is negative and very close to the 0°C isotherm. If the cave would have been strongly ventilated and heat advection played an important role, the fine crystalline variety of CCCs (essentially crystal powders) would have formed instead of the coarse crystalline one. The innovative aspect of our study is the quantitative link between the climate signal recorded by the CCCs to the surface environment.

The references will be added to the manuscript.

Further, the authors could summarize the climatic conditions during the YD in a simplified figure, emphasizing the seasonally distinct climatic conditions and the two-part YD climate and than add their data in support of the inferred climatic conditions. The concluding figure 6 does not clearly supports the authors' claims.

We are not sure why reviewer feels that Fig. 6 is not clearly supporting our claims. We believe that Fig. 5 summarizes these climatic conditions obtained by the heat-flow modeling experiments. We nevertheless appreciate the reviewer´s suggestion and will try to improve this figure.

Specific comments

28 – GS1 starts at 12.9 ka, not 12.8 ka (Rasmussen et al., 2014)

The start of GS1 was at 12.896 yr b2k (Rasmussen et al., 2014), which is 12.846 yr BP.

35 – catastrophic is rather human-centered

We will change this.

37 – perhaps "cold" is enough, Siberian-like is quite subjective (and given that this is a paleoclimate paper, Siberian climate varied widely in the past)

We will rephrase this.

41 – relative to. . .?

Relative to the Bølling-Allerød interstadial (see line 41)

48-52 – to which season do these reconstructions refer?

These reconstructions refer to annual air temperature as stated in line 50.

69-70 – not clear how "enhanced precipitation differences between the northern, central and southern part of the Alps" would result in a YD maximum. Also, check the 13.5 ka age, it is well before the onset of the YD

We will rephrase this sentence for clarification. A new reference will be added for the 13.5 ka BP age (Ivy-Ochs, 2015).

73 – what do you mean by "double response"? Two periods of glacier advance? Please clarify

Yes, we mean two glacier advances as reported by Baroni et al. (2017).

86-88 – I particularly enjoy this statement, but please clarify 1) what do you mean by "strong winter", 2) what season the "1-2 C warming" refers to and 3) the reference for the 'drier" comparative (e.g., "drier" compared to early YD?)

This will be rephrased in the revised manuscript.
For clarification

(1) by strong winter cooling we refer to the 10°C decrease in MAAT compared to present day, as reported from the Jura Mountains (Affolter et al., 2019; Ghadiri et al., 2018), which requires a disproportionally large winter cooling considering that the summer cooling for this part of Europe was rather small as shown by pollen and chironomid data (as detailed in the ms.).
(2) the 1-2°C warming refers to the MAAT
(3) and drier is meant relative to the early YD (as stated in line 89)

91 – This sentence is a odds with the cave's description here

We will remove this sentence.

103-104 – over what period were these snow depth values measured? Snowfall heights do not record the amount if snowfall accurately, please provide the total amount of winter and early winter (September-December) precipitation.

Snow height is monitored in the Dolomites at Rossalm and Piz la Ila stations. Unfortunately, the total amount of precipitation is not measured. We used the monthly data for the last seven years (2012-2019) from Rossalm and for a fifteen-year-observation-period (1999-2014) at Piz la Ila to calculate average snowfall amounts for the autumn (September to December).

114 – What was exactly sampled for stale isotope analyses? Entire CCC? Outer/inner part f it? Please detail.

Most of the CCCs were too tiny to be cut therefore a handheld drill was used to take small aliquots of carbonate powder for stable isotope analyses. Usually, the outer layer was drilled off and discarded and then the carbonate powder was drilled 1-2 mm below the surface. In case of the dated CCC samples, a small aliquot of the drilled carbonate powder was used for stable isotope analyses.

120 – I understand that these CCCs grow over prolonged periods of time. What part of the individual CCCs was sampled for dating? Or was it whole sample?

This is partially explained in the manuscript (line 120-122), and more details will be provided in the revised manuscript. If the single crystals were large enough, the carbonate powder was drilled from the center of the CCC to define the start of CCC formation (15 samples). In case of two skeletal crystals, the entire crystal was used for ^{230}Th dating.

200 – why was a 5 _C temperature chosen for the buffering effect of snow cover?

Please see our response above.

230 – how long does it take for these CCCs to form? Several years is not that much in terms of YD climate variability, so with only 3 ages for the early YD, the inferences made in this article might be slightly far-fetched

The reviewer asks a long-standing question in the community working on CCCs. The short answer is that we only know that the fine crystalline variety of CCCs (essentially crystal powder) forms within a matter of hours to days by comparably rapid freezing of a water film. The coarse crystalline CCC variety – the one we talk about in this study – has never been observed in statu nascendi, and nobody has made experiments growing them under controlled conditions. Still, there is unanimous consensus among colleagues working on coarse crystalline CCC that these carbonates form (a) not within a water film but in freezing pools in the ice, and (b) require much longer to form than their fine crystalline counterparts. This is pretty obvious given the well-developed macroscopic crystals and the fact that in other caves CCC can reach several cm in diameter. There is no published information how much time is involved in the formation of individual coarse crystalline CCC aggregates. In our group we also study Pleistocene CCCs in Siberian caves and they can be up to a few cm in diameter. We dated core and rim of these large CCCs. Even the most precise ^{230}Th ages cannot resolve an age difference within individual CCCs. Considering the age uncertainties up to several hundred years could be involved in the growth history of some of these aggregates. Although the Ciocccherloch samples are significantly smaller than their counterparts from Siberia we are convinced that months to years (and decades in the case of larger particles) are likely involved in their formation. These assumptions are also supported by the smooth isotope and trace element distribution patterns of these particles.

We disagree with the reviewer on the inferences being too far-fetched. During the review process we dated two more CCCs from heaps A and C. These analyses yielded ^{230}Th ages of 12.34±0.2 ka and 12.33±0.2 ka BP, providing further support for CCC formation during the early YD. We strongly believe that neglecting the possibility of early YD CCC formation (as supported by the ^{230}Th ages and their 2σ uncertainties) would be an oversimplification.

235-236 – here is a bit of a jump in logic, as a few lines above (230) a few years are required for CCC to form and now the suggestion is that cave climate was stable for centuries.

We do not see a problem here, and please see our comment above on CCC formation. The majority of ^{230}Th ages overlap within their 2σ errors. Similar prolonged periods of CCC formation have been reported form other alpine caves (e.g. Luetscher et al., 2013; Spötl and Cheng, 2014, Spötl et al., in review)

245 – do you have any indication on when ruble closed the connecting gallery? It could have been open during the YD and hence the cave would have been out of thermal equilibrium with the outside, as discussed above

We have no information on when the rubble closed the narrow connection.

246-248 – I would argue that CCC record changes in the thermal state of the cave, that could be or not in equilibrium with external conditions. The assumption is that the ruble blocking the cave was there throughout and since the YD

We disagree. The presence of a snow cone slightly larger than today could have also sealed this connection. Also, the connection between the CCC-bearing chamber and the entrance shaft could not have been more open in the past than it is today. We provide a discussion on advective processes in lines 283-298.

250-251 – Liquid water reaching the cave would have a dramatic impact on temperature, given the extremely high specific heat capacity of water. I think this is to easily dismissed. And if I understood right, liquid water was required to form CCC (line 259 in the text)

We considered this process qualitatively and concluded that drip water obviously entered this cave chamber forming meltwater pools on the ice, eventually giving rise to CCC formation. This very slow flowing seepage water, however, is likely thermally equilibrated with the ca. 50 m-thick rock above the cave and given its very low discharge carries comparably little heat from the surface. In addition, the YD climate was likely drier than today (as discussed in the ms.) hence discharge was even lower.
We will expand this section to make this point clearer.

264 – U/Th ages show that CCC formed well (several hundreds of years) into the YD, not at the transition.

This sentence will be rewritten.

274 – how likely is that the cave was perennially frozen throughout both winters and summers for several centuries? If not, than the proposed shielding by snow is not required to induce changes in cave air temperature around 0 and thus facilitate the precipitation of CCC

CCC only form very close to 0°C and our data therefore rule out that this cave was well below 0°C during the YD.

277 and subsequent discussion – winter or summer very cold YD? The distinction was heavily promoted in the introduction, it should be made here, as well.

A separate subsection is devoted to the discussion of seasonality changes (5.3 Increased seasonality in the early YD, lines 289-313)

289 – see my comment on the ruble blocking the cave and its effect on cave climate. How was the 3 C temperature obtained?

This maximum amplitude cooling (≤3°C) at the Allerød-YD transition was derived from thermal modeling (scenarios 2c and 2e, please see lines 272-276).

292 and subsequent –warm YD summers indicate that the cave would have been warm enough to lead to ice melting and prevent the all-over freezing of cave. Consequently, CCC could have precipitated by the freezing of water formed during warm summers on the surface of (cold winter forming) cave ice. Is this a likely scenario?

That is an interesting suggestion. Warm summers are accounted for in the modeling experiments (Scenarios 2a-2e). However, we the seasonal temperature signal is cancelled out after the first 10 meters of rock (see the figures showing the heat-flow model results).

CCCs cannot form by repeated thaw-freeze cycles of cave ice as there would not be enough dissolved ions in the water to reach supersaturation via freezing and to precipitate cryogenic minerals. Drip water derive from the epikarst and the vadose zone is needed to deliver the solutes necessary for CCC formation. As slow freezing proceeds, the expulsion of these ions leads to supersaturation and consequently the precipitation of CCCs (e.g. Žák et al., 2012, 2008). This is corroborated by U concentrations much higher than those of warm-climate, non-cryogenic speleothems from the same cave (see Table 1 in the ms.).

303-305 – this shielding would not be required if the scenarios presented above could be happening.

Please see our comment above.

320 – U/Th ages indicate that CCC formed for several centuries, so why the emphasize on this correlation with the mid-YD transition? The age errors and the widespread ages of all CCCs are to large compared to the narrow age of the transition to support the subsequent discussion.

The majority of the ^{230}Th ages cluster at 12.2 ka BP. The weighted mean of all ages is 12.19±0.6 ka BP. As this coincides with the mid-YD transition (12.24 ±0.4 ka BP, see Lane et al., 2013) CCC formation in Cioccherloch Cave was likely connected to this climate event.

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