Comment on cp-2021-106

Anonymous Referee #2

Referee comment on "Late Pleistocene glacial chronologies and paleoclimate in thenorthern Rocky Mountains" by Brendon Quirk et al., Clim. Past Discuss., https://doi.org/10.5194/cp-2021-106-RC2, 2021

This is an interesting study, that combines glacial geology and glacial modelling to infer past glacial conditions in the Northwestern USA. This combined approach (not common in the literature) is always welcome and can provide significant insights regarding the climate evolution of the planet. The scope and structure of the paper is sound, and the outcome could eventually be of major interest for the scientific community. However, the manuscript, in its present form, needs some revision in order to improve some aspects. I would like to invite the authors to consider the comments below, which I hope will help improve the manuscript. Finally, I would like to mention that this manuscript would benefit significantly from a review by a glacial modeler.

General comments:

I am not a native English speaker; however, I can recognize the need for some tidying up of the wording of some sentences throughout the manuscript.

When introducing new areas or sites, please provide coordinates (at least latitudes). People outside the US are not necessarily familiar with the locations discussed in the text.

We have done this.

I am a little concerned with the way that the authors treated outliers (see specifics below). I don´t know if this has a major impact on the main conclusions, but it needs to be addressed consistently.

Agreed. See comments below.

I believe this interpretation does not fully consider the law of superposition. In other words, we have additional context besides the ages themselves, such as distance, elevation and morphostratigraphy, that provide relative age constraints. However, the comment does raise an important point regarding uncertainty analysis. We have performed additional analyses to quantify this uncertainty (see figure below). We adapt the COPRA algorithm (Breitenbach et al., 2012) to quantify the uncertainty in our reconstructed age- distance and elevation transects. Here, we have estimated uncertainty using 10,000 Monte Carlo realizations satisfying superposition.
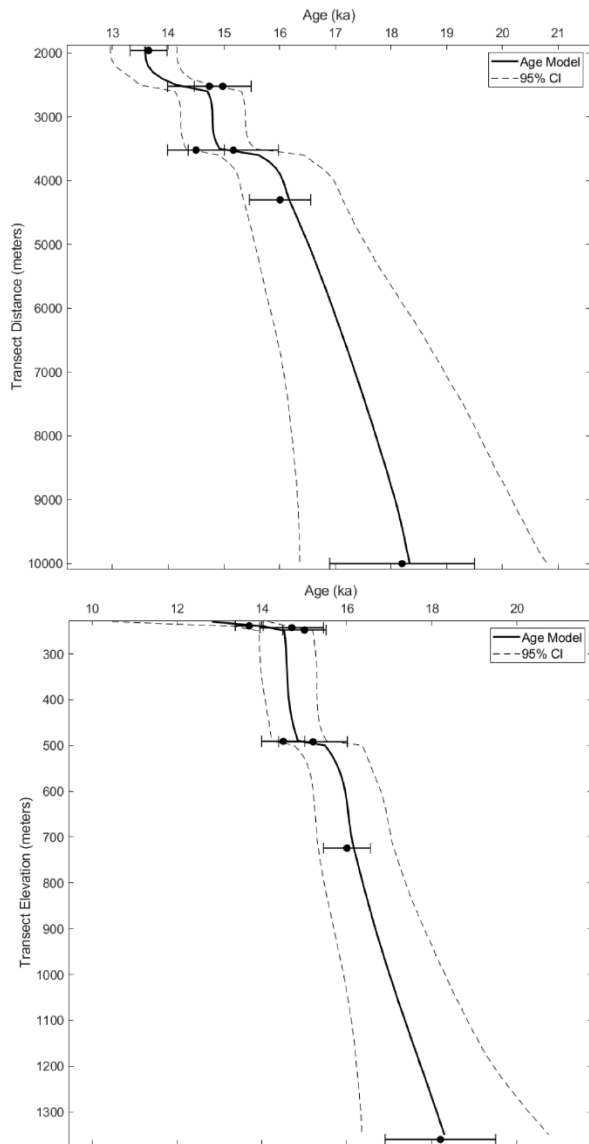
Comments line by line:

INTRODUCTION:

56-58: why is this important? Maybe add 1-2 sentences

We have modified the text as follows: "These spatiotemporally constrained paleo-glaciers can then, in turn, be used to infer paleoclimate conditions in the northern Rocky Mountains during the last glaciation **for which relatively few records exist compared to other regions of western North America**"

84-85 Awkward wording

We have modified the text as follows: "The Lewis Range (48.5°N, 113.5°W) hosted numerous glaciers during the latest Pleistocene and, in some areas, these glaciers coalesced to form the northern Rocky Mountain ice cap (Locke, 1995; Figure 1)".

89-91: this should be in the result section (justified by evidence) or cited from previous publications.

We have cited the relevant publication.

96: what do you mean that they generally flowed down to elevations of 1.6 km? When? 98-101: are we talking during the last glacial cycle?

We have updated the text as follows: "In this study, we focus on the Cut Bank Creek glacier which flowed east from its headwaters at 2.6 km asl and terminated on the piedmont just above 1.4 km asl at its maximum extent. The Cut Bank glacier did not coalesce with either the northern Rocky Mountain ice cap to the west and north or the Laurentide ice sheet to the east during Pinedale times and flowed as a discrete mountain glacier (Calhoun, 1906; Alden, 1932)"

92-101: I am missing citations…. How do you know all this information? (e.g., ice thickness). I couldn´t find a single reference in the Site Description section. Has anyone else worked in the area?

We have updated the section to include the appropriate references.

104: "and relatively little work has been done inferring past climate in the region from paleoglacier characteristics". You should include some examples (cites) at the end of the sentence.

Yes, agreed. In the text as written, the following paragraph cites and describes the published work that has been done on this topic.

Yes. We have updated the text as follows: "No numerical ages are available for these deposits, although a radiocarbon age on a wood fragment, underlying two latest Pleistocene tephra layers in lake sediment at Marias Pass, provides a minimum age of 12,194±145 14C yr (Carrara, 1995) or 13.8-14.8 cal kyr (Fullerton et al., 2004; recalibrated here using IntCal13 (1σ); Reimer et al., 2013) for complete recession of at least one east-side outlet glacier of the Northern Montana Ice Cap in the Glacier National Park region."

Agreed. The text has modified as follows: "Terminal and recessional moraines at the southwestern front of the northern Absaroka Range and in Paradise Valley to the south have cosmogenic 10Be exposure ages that were originally reported by Licciardi et al. (2001) and have been supplemented with additional data from Licciardi and Pierce (2008; 2018)"

We have made this explicit in the text and have modified as follows: "Here, we interpret exposure ages as ice retreat or moraine abandonment ages. Thus, the exposure ages from the Greater Yellowstone glacial system suggest that mountain glaciers began retreating from their terminal moraines during the middle Pinedale and after the end of the global Last Glacial Maximum."

This is a good point considering the Late Pleistocene often refers to time periods much older than those considered here. We have updated the text as follows: "While many investigations in western Montana have focused on reconstructing the extent and chronology of the Pinedale glaciation, fewer have attempted to describe Pinedale climate conditions." Please note that the Pinedale glaciation is defined at Lines 121-124

Agreed, we have updated the text as follows for clarity: "Modern methods used to reconstruct paleo-glaciers, particularly distributed energy/mass-balance or degree-day mass-balance models,

have been successfully applied to sites in the Middle (Laabs et al., 2006; Refsnider et al., 2008; Birkel et al., 2012; Quirk et al., 2018, 2020) and Southern Rocky Mountains (Ward et al., 2009; Brugger, 2010; Brugger et al. 2018, 2019; Dühnforth and Anderson, 2011; Leonard et al., 2014, 2017a; Schweinsberg et al., 2016). In this study we apply a modified version of the Plummer and Phillips (2003) distributed energy/mass-balance model to reconstructed glaciers in the Absaroka and Lewis ranges to help elucidate climate conditions in the northern Rockies during the last glaciation."

METHODS

181-183: move to results

Figure 2: for clarity, please choose a different color for the outline of recessional positions 206: delete "."

255: why did you choose standard error of the mean instead of standard deviation?

It's a better representation of landform age uncertainty as opposed to individual boulder scatter.

269-271: To do that, you need to assume that the moraines in both valleys are coeval, correct? If so, you should mention it in the text. Or am I missing something?

This is discussed in the results section as possible source of error (i.e. temporal offset).

339: A detailed description of the geomorphology of the area is presented; however, it is very difficult to visualize /assess it, given that no detailed geomorphological map is presented (except figure 2 where the authors only depict the moraines)

Yes, we agree with the reviewer's comment. We have included a detailed geomorphological map of the Cut Bank Creek area as the new Figure 4.

356-359: it is unclear to me what the authors want to say here… outer and inner moraines?

We have updated the text for clarity as follows: "The moraines delimit the size and shape of the piedmont lobes formed by glaciers in the two valleys. At Cut Bank Creek, the piedmont lobe had a maximum diameter of 6.8 km while occupying the outer, ice-distal moraine. While occupying the ice-proximal sector, delimited by the mapped recessional moraine, the piedmont lobe was reduced in diameter to approximately 4.4 km and likely became thinner or formed a more gradual slope near the terminus as evidenced by the lower relief along the moraine"

We agree with the reviewer and it was an oversight to not include descriptions of glacier areas and lengths. We have therefore modified the text as follow to include these important metrics: "The moraines delimit the size and shape of the piedmont lobes formed by glaciers in the two valleys. At Cut Bank Creek, the maximum Pinedale glacier, as denoted by the ice-distal moraine, extended almost 30 km from the headwall and occupied an area of ~123 km2 while the piedmont lobe had a maximum diameter of 6.8 km. While occupying the ice-proximal sector, delimited by the mapped recessional moraine, the Cut Bank glacier extended approximately 25 km down valley and occupied an area of 86 km2 while the piedmont lobe was reduced in diameter to approximately 4.4 km and likely became thinner or formed a more gradual slope near the terminus as evidenced by the lower relief along the moraine. The piedmont glacier width was further diminished upon retreat to the recessional moraine to approximately 1.3 km, only slightly wider than the mouth of Cut Bank Canyon . In Lake Creek valley, the piedmont lobe formed an irregular shape, likely due to partial confinement of the northern side of the lobe by the right-lateral moraine in the neighboring Cut Bank Creek valley. The piedmont lobe had a maximum width of about 2.5 km, a total glacier length of 12 km, and occupied an area of 24 km2 when the terminal moraine was occupied. Upvalley of the terminal moraines in Cut Bank Creek and Lake Creek valleys, lateral moraines and other glacial features mapped by Carrara (1989) were used to delimit ice thickness and areal extent."

We understand the reviewer's request. However, and in consideration of the reviewer's other salient comments, we do not think it is appropriate to include the ice-retreat exposure ages on a plot that does not show the spatial relationship between samples. This has, however, been done in Figure 8.

Yes, we agree, there is a lack of consistency in how we determined outliers. Thus we treat DC1204 as an outlier.

This is a good point. We have included a brief description of modern climatology to the 'Site Description' section. More broadly, the modeled precipitation changes are selected in order to define a curve in precipitation-temperature (P-T) space that represents a given glacier stadial. Thus, the individual points need not necessarily be solutions. Further, the P-T curve for a glacier can be modeled with an exponential and it is therefore advantageous to select points spaced reasonably far apart to capture the exponential behavior.

Fig 5: (This comment may be out of ignorance since I am not a modeler) I understand that it is almost impossible to exactly match the modelling results to field evidence, however in panel A I see plenty of room for a bigger drop in temperature, at both the glacier front and headwalls. Can you explain?

Small increases (i.e. tenths of a degree) in temperature depression or precipitation % result in mismatch between simulated and mapped extent – particularly along the piedmont boundary. This is, unfortunately, the best we were able to simulate the paleo-glacier shape.

DISCUSSION

461-464: Actually, 17.5±0.6 ka and 18.2±0.5 ka are statistically indistinguishable. Furthermore, you never discuss if SF Deep Creek and Cascade Creek are coeval or not.

Following corrections for how we determine outliers, text should now address this more clearly: "The 10Be exposure ages presented here for the South Fork Deep Creek (18.1 ± 0.1 ka) lateral moraine agree well with the landform age from the previously dated lateral moraine in the neighboring Pine Creek valley in the northern Absaroka (10Be exposure age = 18.2 ± 0.5 ka, with the standard error of ages recalculated from Licciardi and Pierce, 2008). The Cascade Creek (16.9 ± 0.1 ka) moraine exhibits a younger age than both the South Fork Deep Creek and Pine Creek moraines. However, and as previously discussed, the Cascade Creek moraine exposure ages should be considered preliminary due to relatively high analytical uncertainties. Although these moraines were deposited by discrete valley glaciers, their exposure ages are similar to 10Be exposure age of the nearby Eightmile terminal moraine (17.9 ± 0.4 ka, recalculated from Licciardi and Pierce, 2008), the outermost moraine of the last glaciation deposited by the northern outlet glacier of the Yellowstone Icecap, as well as to the age of the Chico moraine (17.1 ± 0.6 ka recalculated from Licciardi and Pierce, 2008) the initial moraine deposited during recession of this outlet glacier. These ages for the outermost and initial recessional moraines in the northern Yellowstone/northern Absaroka Range area in southwestern Montana are also very similar to those we report here for the terminal (17.2 ± 0.2 ka) and initial recessional (16.4 ± 0.2 ka) moraines at Cut Bank Creek in northwestern Montana. Taken together, these ages suggest that terminal moraines in western Montana were occupied until ca. 18-17 ka and that glaciers

were still near their maximum lengths at ca. 17-16 ka in northern Yellowstone and in the Lewis Range, as indicated by exposure ages of the recessional moraines."

541: of the for the…. Review this sentence 668-670: citations for CO2 increase?

We have corrected the typo, thank you for pointing it out. We have included references to the CO2 data in the text and figure caption.