Reply to ‘Review’ from RC 1 Richard Selwyn Jones

We thank RC 1 for their thoughtful and constructive review of our manuscript. We have gone through and replied to each individual comment. Below, please find the original comments bolded and italicized and our reply in normal font.

Detailed comments

Lines 123-125: It is not clear from this sentence whether the estimate that “glaciers remained at (100%) or near (82-83%) their LGM length until 16-15 ka” is derived by this study or a previous study.

While we measured the normalized moraine locations in this paper, the age ranges for the moraines between 16-15 ka were established in previous studies that dated those moraines. We have re-arranged this portion of the text, in accordance with both yours and RC 2’s suggestion to read:

“The moraine chronologies reported thus far reveal that following the LGM (which culminated between ~22 – 19 ka), a recessional moraine at 82% of the LGM position sampled in the Lake Creek system was deposited at 15.6 ± 0.7 ka (Schweinsberg et al., 2020). There is a similar-appearing moraine at 83% of the LGM position in Clear Creek valley. Although it is undated, we tentatively correlate this moraine in Clear Creek valley to the moraine dated to 15.6 ± 0.7 ka in Lake Creek valley. Finally, there is no recessional moraine in Pine Creek valley, but a cluster of ages at 16.0 ± 0.9 ka from the LGM moraine suggest that the glacier re-advanced to or remained at its LGM extent until nearly the same time when glaciers in the other two valleys deposited recessional moraines (Briner, 2009; Young et al., 2011).”

Lines 139-145: Hypsometry is the only named non-climatic factor that is considered. Were these glaciers ever lake-terminating (e.g. Lake Creek)? What role could bed geometry have played?

While we recognize that there are lakes present in both Lake Creek and Clear Creek, these are dammed reservoirs and may or may not have been present at the time of deglaciation. Whether or not glaciers may have been lake-terminating near their terminal moraines, our focus is on glacier retreat upvalley, which would not have been influenced by terminal-moraine-area lake effects. Thus, the majority of retreat commenced in these valleys without any possible influence from lake-terminating dynamics. Even if lakes did exist, and dynamics associated with lakes is likely not among the explanations for any inter-valley variability.

To the point of bed geometry, we should be more explicit in describing how the retreat rates are influenced by valley geometries/hypsometry. We find that the retreat rates are significantly different between each valley and we wonder if this is attributable to valley geometry/hypsometry. The smallest, shortest and steepest valley (Pine Creek) retreats at the slowest rate while the other two valleys which are broader and much larger retreat at faster rates. As mentioned in our response to SC 1, we find there may have been some notable non-climatic factors that influenced when glaciers began initially retreating, and perhaps even the rates of retreat among the different valleys, but we think that the ~1 – 1.5 kyr of synchronous retreat across all three valleys is strong evidence for a climatic driver.

As mentioned in our reply to the short comment in the open discussion, we are adding in a brief discussion of retreat rates and average valley gradients and how the two scale, as well as appending the concluding statement at Line 269:

Starting at Line 217: “The calculated average valley gradients for each valley – measured as the elevation change divided by the horizontal length of each valley bottom transect from LGM moraine up to the base of each respective cirque – are 29 m/km for Lake Creek valley, 37 m/km for Clear Creek valley, and 65 m/km for Pine Creek valley.”

Starting at Line 269: “We also observe that Pine Creek valley has the steepest average valley gradient and the slowest net retreat rate, which is predictably a direct result of valley hypsometry since glacier lengths in steeper valleys generally adjust less to equivalent changes in ELA. On the other hand, glaciers occupying the lower-gradient Lake and Clear creek valleys experienced higher reconstructed rates of retreat. Regardless, we find that while Pine Creek may have initiated ~500 yr sooner than the other two, all three valleys were in a period of ~1-1.5-kyr-long synchronous retreat once the other two glaciers began retreating. We conclude that while there may have been some hypsometric influences on the timing of deglaciation across our study site, evidence suggests these influences did not keep these glaciers from synchronously retreating during a majority of their deglaciation.”

Line 150: The text refers to a “slightly modified” method. Modified from what – Corbett et al. (2016)? Modified how?

The differences in the procedure between our lab and the UVM lab are very minor and likely not worth mentioning. We have elected instead to simply remove the phrase “slightly modified”

Line 155-160: What was the ratio/^{10}Be concentration of your procedural lab blank(s)?

We updated the text to include that information:

“After quartz purification, samples were dissolved in acid along with a ^{9}Be carrier spike in two batches each with a process blank.”

And

“For samples collected in 2018, the process blank $^{10}Be/^{9}Be$ ratio was 2.96 x 10-15, and for samples collected in 2017 the process blank $^{10}Be/^{9}Be$ ratio was 9.56 x 10-16 (see Table 1 for details on sample collection dates).”

In addition, we added a footnote to Table 1 listing the process blank values.

Lines 175-179: This isn’t the first time that Bayesian age-depth models have been used for transects of ^{10}Be ages. Previous such work (e.g. Jones et al., 2015, Nat. Comms.; Small et al., 2018, GSA Bull.) should be acknowledged. In general, the approach to derive retreat rate estimates needs more detail. What is exactly being modelled here? Is it assuming a linear or non-linear relationship between age and depth/distance? Is the model accounting for age uncertainties? If so, are the age uncertainties included at 1 or 2 standard deviations, weighted or unweighted?

Thank you for bringing these additional citations to our attention. We tried to be as thorough in acknowledging that this type of work has been published before so we are happy to include these citations in the list cited at the end of the first introduction paragraph.

As to describing BACON with slightly more detail, we amended the mentioned paragraph to now read:

“To calculate retreat rates, we used the BACON program in R (Blaauw and Christen, 2011). This program generates age-depth models for stratigraphic records based on chronologic constraints at various depths. Here, we use the 10Be ages and their 1-sigma uncertainties measured in each valley as the age input and the geographic coordinates of each age as the depth inputs. The position along the valley floor is scaled such that the toe of the glacier at the LGM is the starting point (e.g., 100% or maximum length), and the base of each valley’s cirque wall is the end point (e.g., 0% or minimum length). The model then interpolates between each point using Bayesian analysis and the geologic principle of superposition to build an age-length model with an unweighted statistical treatment of uncertainty. The interpolation between points is smoothed (i.e. non-linear) based on retreat rates at previous positions. The retreat rates presented here are net retreat rates, because it is possible there may have been short-lived re-advances that did not lead to significant moraine deposition. BACON outputs a time series of age-length points and non-Gaussian 95% confidence intervals. Calculated retreat rates are assumed to be linear, and we report the 95% uncertainty range.”

Lines 183-184: Clarify what you mean by “net retreat rates”.

We use the term “net” retreat rates because there may be many short-term re-advances “hidden” in our chronology, short events that are un-detectable by our chronology. Thus actual retreat rates could have been higher locally. We believe that “net” retreat rate is an appropriate way to characterize our derived retreat rates.

Results: You should initially report the results for only the new data (the 12 ages from Clear Creek and Pine Creek), even if only described briefly. After that, you can describe the results in combination with the previously published ages.

We added the following sentence to the beginning of the paragraph:

"The 12 new sculpted-bedrock 10Be ages reported here range 15.8 ± 0.3 – 13.7 ± 0.3 ka (Fig. 2; Table 1)."

We also update Table 1 and Figure 2 to identify which samples are new and which samples are previously published.

Line 190 (and elsewhere): How confident are you in the precision of your distance measurements? Would rounding to the nearest whole percent be more suitable?

We measured profiles along valley floors in ArcGIS to get precise numbers, but we agree that rounding to the nearest whole percent is more realistic. We fixed this throughout the text and in Table 1.

Line 214 (and elsewhere): Please clarify here whether the retreat rate result is reported at 68% or 95% confidence. Additionally, the format of reporting is probably not suitable, as the model output distribution is likely non-Gaussian. Such results are therefore typically reported as an uncertainty range, rather than mean with uncertainty.

We appreciate the insight on reporting model outputs that you correctly pointed out are non-Gaussian. We now report the 95% uncertainty range throughout the text.

Lines 233-243: The identification of likely outliers is based on the general stratigraphic relationship of ages within the dataset. These outliers also happen to fall outside of the 95% confidence bounds from the BACON model. But, as far as I can tell, BACON was not used to systemically identify (and remove) outliers. In which case, the estimated retreat rates from BACON will be influenced by these apparent outliers. So, how do the retreat rates differ when these outliers are excluded?

When calculating the resulting retreat rates if we remove outliers and in all three valleys, the retreat rates decrease by 1.7, 2.7 and 6% for Lake Creek, Clear Creek and Pine Creek valleys respectively. We have added the following sentence:

"Removal of potential outliers reduces retreat rates by 1.7%, 2.7% and 6% for Lake Creek, Clear Creek, and Pine Creek valleys respectively."

Lines 247-252: More of a discussion point than a criticism: While it seems fairly well justified to use the Promontory Point calibration site instead of NENA site based on locality and elevation range, it is also worth considering the time period

used for the calibration sites. The Promontory Point site is calibrating the production rate at 18.9- 18.0 ka, while the NENA site is calibrating for 16.8-13.8 ka. The dataset reported here best correlates to the time period covered by the NENA site, which could be an argument to use this production rate instead of that from Promontory Point.

This is a good point – production rate choice is always a topic of discussion. Fundamentally, this is why we provide our ages with two reasonable production rate choices. As the reviewer knows, ultimately, you have to choose one to go with for the main text. While we agree that there are advantages to dating features close in age to a calibration site, it is likely that other factors (as mentioned in the text) like site elevation, are also important. Ultimately, the age ranges at the PPT and NENA calibration sites are fairly close in age to ours. That said, because PPT is the closest in elevation to our field area, and is a rate that others are using in their papers for Rocky Mountain cosmogenic nuclide chronologies, we chose to report PPT in our text.

Lines 266-269: Explain how glacier hypsometry and/or steepness would influence differing glacier behaviour during deglaciation.

We are adding in a brief discussion of retreat rates and average valley gradients and how the two scale, as well as appending the concluding statement highlighted at the beginning of our response:

Starting at Line 217: “The calculated average valley gradients for each valley – measured as the elevation change divided by the horizontal length of each valley bottom transect from LGM moraine up to the base of each respective cirque – are 29 m/km for Lake Creek valley, 37 m/km for Clear Creek valley, and 65 m/km for Pine Creek valley.”

Starting at Line 269: “We also observe that Pine Creek valley has the steepest average valley gradient and generally the slowest net retreat rate, which is predictably a direct result of valley hypsometry since glacier lengths in steeper valleys generally adjust less to equivalent changes in ELA. On the other hand, glaciers occupying the lower-gradient Lake and Clear creek valleys experienced generally higher reconstructed rates of retreat. Regardless, we find that while Pine Creek may have initiated ~500 yr sooner than the other two, all three valleys were in a period of ~1-1.5-kyr-long synchronous retreat once the other two glaciers began retreating. We conclude that while there may have been some hypsometric influences on the timing of deglaciation across our study site, evidence suggests these influences did not keep these glaciers from synchronously retreating during a majority of their deglaciation.”

Lines 285-288: Glaciers don’t respond to CO_2, so directly comparing to CO_2 seems a little irrelevant. Of course, there is a close relationship between CO_2 and temperature, but why not compare your glacier retreat records to proxy global temperature (e.g. Shakun et al., 2012)?

We thank the reviewer for highlighting this. We have changed the text and Figure 5 to show the proxy global temperature curve compiled in Shakun et al., 2012. We also recognize that the compilation curves from Shakun et al. are clearly influenced by more than just greenhouse gas forcing, particularly in the Northern Hemisphere. It may be argued that the southern hemisphere compiled record is more closely tied to atmospheric CO_2 concentrations so we are including both the global record and the southern hemisphere records in figure 5.

Lines 327-334: The argument that there is similarity between records, and "possible teleconnections", isn't particularly convincing. The majority of the recorded retreat occurred before the North Atlantic climate shift; your ages indicate retreat initiated 1-2 kyr earlier that the climate shift at 14.7 ka. I'd like to see the text rephrased, without mention of teleconnections.

As you observe, the glaciers in our field site do begin retreating prior to the onset of North Atlantic abrupt warming. Originally we were more focused on the fact that the rate and short-lived nature of retreat was most similar to the abrupt North Atlantic warming even though the timing was not perfect. And so, we removed mention of teleconnection since it is difficult to argue that glaciers retreated in response to N. Atlantic warming if they were already retreating prior to the abrupt warming event.

Rather, we reworded the section to read:

"We find that deglaciation at some locations in the southern Rocky Mountains encompasses the HS-1/Bølling transition. Furthermore, the relatively rapid and short-lived nature of retreat for glaciers in the Sawatch Range – and some others across the Southern Rocky Mountains – appears to be more consistent with the abrupt manner of warming observed in the North Atlantic. However, glaciers apparently were already retreating prior to the abrupt HS-1/Bølling transition at ~14.7 ka. Therefore, it is difficult to argue that North Atlantic warming alone forced glacier retreat in the Southern Rocky Mountains."

We also appended a few sentences in the abstract to read:

"Deglaciation in the Sawatch Range commenced ~2 – 3 kyr later than the onset of rising global CO_2, and prior to rising temperatures observed in the North Atlantic region at the Heinrich Stadial 1/Bølling transition."

Lines 329-330: What is this period of relative glacier stability based on?

Our original line of thought was that, based off of the previous moraine chronologies at our field site, it is possible that glaciers remained at relatively stable positions from the culmination of the LGM up until they began retreating at 16 – 15 ka. However, it is also possible that glaciers retreated in this time frame and then re-advanced to form the moraines deposited at 16 – 15 ka. We do not know which scenario is correct so we elected to remove this sentence.

Line 383: "one of two", or both mechanisms, as you state below. Reword this, as these are not mutually exclusive explanations.

We rephrased the sentence with the following: "we hypothesize that one of two – or a combination of both – possible regional climatic mechanisms…"

Lines 385-386: As mentioned above, it is a difficult to accept that the glaciers "began retreating around the time of abrupt warming" when the data indicate retreat started at least 1-2 kyr before the climate transition. There is only correlation here if you doubt the accuracy (or precision) of the retreat ages, in which case you should discuss more thoroughly.

Re-worded the text here to read as follows:

"First, we find that for some alpine glaciers in the region, the relatively rapid, short-lived and synchronous nature of retreat – including those in the Sawatch Range – across the southern Rocky Mountains is more consistent with the abrupt manner of warming observed in the North Atlantic than with increasing global temperature forced by CO_2 rise. However, evidence suggests glaciers were already retreating prior to the HS-1/Bølling transition."

Lines 387-390: I like the comparison of the rates of glacier and climate change, as it makes use of your estimated retreat rates and it can be effective if there is any doubt in the absolute timing. However, a number of non-climatic, glaciological processes can also contribute to faster rates, even with a gradual forcing. Such processes also need to be considered.

We agree that the rate of retreat can be modified by non-climatic factors. And this is in fact supported by the relationship between retreat rates and valley gradients that we previously discussed. However, that all three neighboring glaciers evacuated their valleys in the same 1-2 kyr interval in time, relatively quickly despite the variation in retreat rate, we believe must be climatically forced.

Line 400: Sorry to be pedantic, but as above, glaciers don't respond to gas concentrations. Refer to global temperature instead.

Changed the wording here and elsewhere to say, "increase in global temperature forced by CO_2 rise"

Table 1: Transact distances are reported to the nearest metre over many thousands of metres. This seems unrealistically precise.

As previously stated, we now round.

Figure 2: Need to make clear what are the new data and what are previously published data. There are also two references to "n=x", which I presume need values added.

Closed circles are now previously published ages and open circles are new ages in the figure.

The references to n = x in both cases have been resolved.