Response to Reviewer 1 (Dr. Matteo Spagnolo)

RC = Reviewer Comment

AR = Author Response

RC 1	Dear Editor and Authors, I read with great interest this manuscript, which attempts to chronologically constraint the post-Tioga4 deglaciation in the Sierra Nevada, linking it to key palaeoclimatic events that likely drove a relatively rapid and widespread glacier retreat in this region. The quality and quantity of the work undertaken and presented is truly impressive. The authors have really considered many different aspects which could have impacted the results and looked at these in great detail. A good number of other proxies are also revisited and considered to strengthen their interpretation. The implications from a paleoglaciology and palaeoclimatology point of view are important. And the topic is certainly of interest to a wide international audience. All in all, I therefore encourage a swift acceptance for publication of the submitted manuscript. However, I believe there are a number of potential improvements, the most important ones I list below, in no particular order. I consider these of a minor nature, and I believe it should take relatively little effort to address these. Notice that I will also attach a version of the manuscript with some 55 comments and additional edits, which might be useful to improve the manuscript too.
AR 1	Dear Dr. Spagnolo: Thank you for these encouraging words and suggestions for improvement!
RC 2	1. The manuscript is too long. I appreciate there is a lot to talk about, but to make it as attractive as possible to a wide audience I recommend some trimming. Could some aspects be moved the supplementary material? For example, do we really need such long narrative around the age calculations (though I appreciate the destination journal somewhat justify it)? Could this be moved to the supplementary and referred to in the main text?
AR 2	The manuscript is indeed long – and we accept the wisdom of moving some of the material (such as the discussion regarding the age-calculation methods) to the supplement, which will be reflected in our revised version.
RC 3	2. A clearer justification of the main research focus, i.e. duration of deglaciation (rather than what most other cosmo glacio papers deal with, that is moraine ages). Why does it matter?

AR 3	The manuscript has three foci: (1) determining which cosmogenic surface-exposure calculator is producing ages most consistent with the radiocarbon dates on the timing of the Tioga 4 deglaciation, (2) applying the preferred set of ages to determine the timing and duration of the Tioga 4 deglaciation, and then (3) placing that timing (and that duration) in a larger context via a reanalysis of regional (and remote) paleoclimate proxies. We will emphasize this more clearly in the text. Our principal motivation in attempting to constrain the Tioga 4 deglaciation's duration is motivated by the question *What can we reasonably infer about the past from the* ^{10}*Be concentration of scattered boulders in this formerly glaciated landscape?* That said, a quantitative reconstruction of deglaciation's duration is a jumping off point for reconstructing the minimum rate of equilibrium-line altitude (ELA) rise (e.g., Vacco et al., 2010). We will make this point more explicit in a revised version of the manuscript. Additionally, as the manuscript currently notes, deglaciation's duration provides a maximum constraint on the duration of the climate change that drove the deglaciation – although we do not think this maximum constraint is closely limiting.
RC 4	3. Is there a wider lesson to be learned, which could be of relevance to other palaeoglaciology/climatology studies elsewhere, i.e. not specific to the Sierra or North America?
AR 4	Thank you for this prompt; we see <u>two wider lessons</u> to be learned from this manuscript: 1. **Geochronometer Considerations:** The three cosmogenic surface-exposure calculators we consider here produce ages that are offset by 5% on average despite identical inputs. For researchers working elsewhere, they should consider whether their interpretations are calculator dependent. 2. **Paleoclimate Inferences:** The timing of rapid deglaciation in the Sierra Nevada (USA) is indistinguishable from the timing of Heinrich Event 1 (HE1) in the North Atlantic, which suggests a causal link between the two. For researchers working elsewhere on the ca. 16 ka time period, they should consider whether this atmospheric reorganization also impacted their field area. In our revised version, we will include more explicit language to emphasize and better summarize these primary points.
RC 5	4. Somewhat related to point 1, though I appreciate the effort, I think that the work undertaken to establish snow shielding is a bit of an overkill, given that

	ultimately we have very little knowledge of how this varied in the past. Can the past 50 or a 100 years or even a few centuries be truly representative of conditions over a timeframe 2 orders of magnitude longer? I suggest the text that relates to this is reduced considerably.
AR 5	Extrapolating snow conditions in the Sierra Nevada from the last ~50-100 years to the last *ca.* 16,000 years is indeed a challenging – but a snow correction is clearly required for developing an absolute chronology (see, for example, Fig. 2-5 in the lead author's dissertation) and extrapolating from recent snow observations to the distant past is the most commonly used approach to solving this problem (e.g., Gosse and Phillips, 2001). Moreover, recent snow conditions in the Sierra Nevada (*i.e.*, the last ~50-100 years) seem to be reasonably representative of average snow conditions over the last *ca*. 16,000 years. For example, if *no* snow correction is applied to the ages, then variations in boulder height explain ~30% of the age variations between the samples (depending on choice of calculator (Fig. 2-5 in Becker's dissertation). However, if we (1) apply a correction for seasonal snow shielding and (2) assume it is equal to historical snow conditions in the Sierra Nevada (since ca. 1946), then boulder height explains <1% of the age variation. And, unlike in most other surface-exposure dating studies that use historical snow conditions to correct for snow conditions over the postglacial interval, we propagate the modern uncertainties in snow-water equivalent (SWE) vs. elevation (Fig. S21 in the manuscript) and in average snowpack density vs. SWE (Fig. S22c) into our preferred set of cosmogenic surface-exposure age uncertainties for this study (*i.e.*, those from the CRONUScalc 2.0 (Marrero et al., 2016) calculator). Thus, compared with most previous cosmogenic surface-exposure dating studies that use historical snow conditions to correct for snow shielding over the "post-glacial interval" (however long that interval might be), the approach we describe in this manuscript a more comprehensive treating of this uncertainty and thus is more likely to be representative of that longer interval (the past *ca*. 16,000 years in this case) than the reported age uncertainties in those other publications. All this said, while we wish to preserve the supplement's detailed description of the snow-shielding correction – because future work (including some of our upcoming work) would like to cite back to this paper – we have made the following changes to shorten the supplement: 1. We have moved Tables S4–S6 from the supplement to GitHub; the supplement now contains links to these tables in Excel and pdf formats. 2. In Section S.5.1.1., we refer readers to Appendix B of Becker's dissertation for a description of how the daily snow-water equivalent (SWE) records were cleaned.

	3. We have moved Figures S11–S19 from the supplement to GitHub; the supplement now contains links to these figures. Figure S10 is retained in the supplement to give readers a flavor for the information that these figures contain. Collectively, these three changes have shortened the portion of the supplement devoted to the snow-shielding correction by 50 %, from 24 pages to 12, while preserving all the information that was in it before.
RC 6	5. Please try to steer away from the description of glacial dynamics in terms of percentage of LGM glacier length and use ELA instead, even if transient (not connected to a moraine), which is far more important and robust glacier mass balance wise.
AR 6	We agree with this suggestion and we will replace most of our "percentage of LGM glacier length" estimates with toe-to-headwall-based ELA reconstructions. With regards to the Tioga 4 readvance, previous authors have noted that it extended to ~60 % LGM-glacier length (e.g., Clark, 1976; Clark and Clark, 1995; Phillips et al., 2009), and we would prefer to retain mention of this relative length in the introductory sections of the manuscript for consistency with the previously published literature, while supplementing it with ELA reconstructions.
RC 7	6. Could you quantify a retreat rate? This will help putting your "rapid and abrupt" deglaciation into context.
AR 7	Yes, these rates were reported in Becker's dissertation and we will include those values in our revised manuscript.
RC 8	7. Figure-wise, all great and useful. Dare I ask you to consider providing a 3D cartoon-like/schematic diagram showing the glacier retreating through the studied sites, exemplifying key geomorphological/geological evidence that justify your conclusion along with the ages of the various samples? These diagrams could perhaps be added to figs 3-5.
AR 8	Our concern with providing a 3D cartoon-like / schematic diagram that shows the various phases of glacial retreat is that these cartoons would be fairly unconstrained with regard to volumetric changes and would be more accurate if informed by a numerical model of ice-extent through deglaciation. Figures 3-5 provide what is perhaps the best reconstruction of our glacial changes and what we are most comfortable providing at this point.
RC 9	Looking forward to seeing this great work published as soon as possible, Matteo Spagnolo

AR 9	Thank you for your encouraging remarks.
RC 10	**The remaining reviewer comments in this document come from an annotated copy of the preprint with 56 comments by Dr. Spagnolo.** Screenshot from the preprint… 0.4 ka and drying at 16.20 ± 0.13 ka. Collectively, we interpret that rapid deglaciation began at 16.20 ± 0.13 ka. This timing is indistinguishable from that of Heinrich Event 1 (HE1), which Comment: I would delete this point. It seems to contradict your earlier statement: "These dates indicate rapid deglaciation began at 16.4 ± 0.8 ka and lasted for ca. 1.0 kyr.". With relation to the timing of these two climatic signals, the deglaciation could have, and likely did, started with the slightly-earlier warming at 16.4. All ages here are very much compatible, given their error.
AR 10	Thank you for bringing this issue to our attention. We will delete this sentence and otherwise modify the abstract so it reads: "A polar jet stream (PJS) split by the Laurentide Ice Sheet (LIS) is a well-established feature of Ice-Age atmospheric circulation in many general circulation models. California's central Sierra Nevada Mountains (37–38° N) lie near the reconstructed position of the PJS's southern branch. Previous glacial studies concluded that rapid deglaciation began here at ca. 16–15 ka after millennia of relatively glacial stability at ~60 % Last Glacial Maximum glacier length. However, this conclusion is largely based on the behavior of glaciers in a single valley (Bishop Creek Canyon). Here, we report 31 new ^{10}Be-derived ages from two locations (Lyell Canyon and Mono Creek Canyon) and 26 recalculated ^{36}Cl dates from Bishop Creek Canyon. These dates indicate rapid deglaciation began at 16.4 ± 0.8 ka. Placing two previously published paleoenvironmental reconstructions with centennial resolution on revised age-depth models, we also find evidence for coeval warming in the central Sierra Nevada at 16.4 ± 0.4 ka and drying at 16.20 ± 0.13 ka. Collectively, we interpret that rapid deglaciation began by 16.0 ka. This timing is indistinguishable from that of Heinrich Event 1 (HE1), which occurred between ca. 16.5 ka and ca. 15.9 ka. We hypothesize that the Sierra Nevada's deglaciation was driven by a northward repositioning and focusing of the winter-storm track over western North America in response to PJS reunification, bringing warmer and drier weather to the central Sierra Nevada, and that PJS reunification occurred in response HE1 thinning the LIS."
RC 11	Screenshot from the preprint… western North America in response to PJS reunification, bringing warmer and drier weather to the central Sierra Nevada, and that PJS reunification occurred in response HE1 thinning the LIS.

	Comment: to
AR 11	Thank you for catching this typo. We have now made the change.
RC 12	Screenshot from the preprint… et al., 2010a; Laabs et al., 2011; Rasmussen et al., 2014; Bahr et al., 2018; Barth et al., 2018; Pedro et al., 2018; Li and Born, 2019). Comment: Given the focus of the paper, it would be really important to add a sentence here on how studies on deglaciation rates could play a role in this general goal
AR 12	This manuscript's focus evolved as it was drafted – and in hindsight we think the submitted version retained too much emphasis on providing readers with a single, probabilistic estimate for the duration of the Tioga 4 deglaciation, given that its duration (as we define it) would have varied with local ice thickness. While we wish to keep this material as an ancillary point within the manuscript, we do not think the estimate is of sufficient importance to justify a sentence within the Introduction's opening paragraph. Rather, we will add a sentence on the utility of deglaciation-duration estimates to paleoclimate reconstructions to what is currently the Introduction's fourth paragraph, which introduces the duration of the Tioga 4 deglaciation as an important concept within the manuscript.
RC 13	Screenshot from the preprint… Field-based studies in the Sierra Nevada Mountains (USA) – such as geomorphic observations (Clark, 1976; Clark and Clark, 1995) and ^{10}Be, ^{26}Al, and ^{36}Cl surface-exposure Comment: A sentence or two, perhaps on N America, connecting the first global perspective paragraph and this very detailed, Sierra focused one would improve the narrative of the intro.
AR 13	Yes, we agree. Because this manuscript focuses on Heinrich Event 1 and how it indirectly drove the Tioga 4 deglaciation, and Heinrich Events were mentioned in the opening paragraph, we will use Heinrich Events as the transition from the first to second paragraphs of the Introduction.
RC 14	Screenshot from the preprint… dating (James et al., 2002; Phillips et al., 2009) – indicate that the range's glaciers responded strongly to a large and abrupt change in climate near the end of the last deglaciation. After Sierra Comment:

	can you be more specific?
AR 14	Yes, we will modify this sentence so it includes the dates that James *et al.* (2002) and Phillips *et al.* (2009) inferred for this climate transition.
RC 15	Screenshot from the preprint… strongly to a large and abrupt change in climate near the end of the last deglaciation. After Sierra Nevadan glaciers reached their greatest extents, broadly in-phase with the global Last Glacial Maximum (LGM; Phillips et al., 2009; Rood et al., 2011), they receded for several thousand Comment: provide a time range for this, for those who might not be familiar with the glacial history of our planet
AR 15	Yes, we agree that providing a numeric age for the LGM would improve the accessibility of this manuscript.
RC 16	Screenshot from the preprint… Maximum (LGM; Phillips et al., 2009; Rood et al., 2011), they receded for several thousand years – with episodic advances superimposed on this general trend – before readvancing to ~60 % LGM-length. Glaciers in the Sierra Nevada rapidly melted following this readvance (Clark, Comment (on "before readvancing"): when?
AR 16	Phillips (2016) interprets that the Tioga 4 readvance began at *ca.* 16.8 ka. We'll add that age and reference to this sentence (or otherwise revise the paragraph such that it is included).
RC 17	Screenshot from the preprint… % LGM-length. Glaciers in the Sierra Nevada rapidly melted following this readvance (Clark, 1976; Clark and Clark, 1995), receding from ~60 % LGM-length to ~~<3 km length (0–23 %~~ Comment: how many glaciers? How widespread and generally accepted is this conclusion?
AR 17	At least fourteen glaciers in the Sierra Nevada and one in the White Mountains deglaciated in response to the climate change that drove the Tioga 4 deglaciation. These fifteen glaciers span 290 km of the range, from Old Man Mountain in the north at 39.4° N to the South Fork of Bishop Creek Canyon at 37.2° N. The conclusion that Sierra Nevadan glaciers rapidly melted following the Tioga 4 readvance is generally accepted by those who have studied the range's deglaciation (e.g., Clark, 1976; Nishiizumi et al., 1989; Clark and Clark, 1995;

	Phillips et al., 1996, 2009; Evans et al., 1997; James et al., 2002; Clark et al., 2003; Gillespie and Clark, 2011; Phillips, 2016, 2017; Putnam and Hatchett, 2017).
RC 18	Screenshot from the preprint… % LGM-length. Glaciers in the Sierra Nevada rapidly melted following this readvance (Clark, 1976; Clark and Clark, 1995), receding from ~60 % LGM-length to ~~<3 km length~~ (0–23 % LGM-length) in "500 yr or less, and certainly less than 1000 yr" (Phillips et al., 2009, p. 1031). Note: RC 18 is about the struck-out text, not the highlighted text and associated comment.
AR 18	We will reword this sentence such that it is compatible with the reviewer's suggestion to steer away from describing glacier-length variations and instead focus on ELA variations, as described in RC/AR 6.
RC 19	Screenshot from the preprint… % LGM-length. Glaciers in the Sierra Nevada rapidly melted following this readvance (Clark, 1976; Clark and Clark, 1995), receding from ~60 % LGM-length to ~~<3 km length~~ (0–23 % LGM-length) in "500 yr or less, and certainly less than 1000 yr" (Phillips et al., 2009, p. 1031). Comment: what is this chronology based on? Is the 1-23% connected with the Recess Peak, which was a few millennia later?
AR 19	This chronology is based on the average age difference between ^{36}Cl dates from the Tioga 4 moraine in the Middle Fork of Bishop Creek Canyon and from boulders in Humphreys Basin. Humphreys Basin is a relatively expansive (~17 km^2), low-relief (~200 m), high-altitude (~3,350–3,550 m) region between the cirques and the glacially eroded U-shaped valleys (37.265032, -118.706515). The five ^{36}Cl dates on boulders from Humphreys Basin date the end of large-scale deglaciation in the Sierra Nevada (Clark and Gillespie, 1997; Phillips et al., 2009; Phillips, 2016). Yes, the 1–23 % statement is connected with the Recess Peak glacial advance. The 23 % LGM-glacier length statement is based on the glacier that was east of Mount Barnard. During the LGM, this glacier was 5.13 km long and during the Recess Peak glacial maximum it was 1.20 km long (Moore, 1981). To clarify our point, we will update the manuscript with ELA estimates, as we think these will better describe the climate changes associated with these glacial advances and retreats than the percentage-of-LGM-length statistics.
RC 20	Screenshot from the preprint…

	This readvance and subsequent deglaciation suggest two reorganizations in atmospheric circulation over the northeastern Pacific Ocean. An earlier reorganization that brought cooler Purple Comment: final Orange Comment: this implies a pre re-organisation circulation of sort which has not been described
AR 20	With regards to the purple comment, we will revise this sentence for greater clarity, as suggested. With regards to the orange comment, yes, there would have been some sort of atmospheric circulation pattern over western North America, then there was an atmospheric reorganization at ca. 16.7 ka (Phillips, 2016, 2017) that brought cooler summers and wetter winters to the Sierra Nevada, driving the Tioga 4 readvance, and then at ca. 16.2 ka there was another atmospheric reorganization that brought warmer summers and drier winters to the Sierra Nevada. Based on the response of Sierra Nevadan glaciers to that second reorganization – widespread and rapid deglaciation – we infer that the second atmospheric reorganization was a larger magnitude event than the first reorganization.
RC 21	Screenshot from the preprint… circulation over the northeastern Pacific Ocean. An earlier reorganization that brought cooler summers and/or wetter winters to the Sierra Nevada (driving the readvance) and a later, larger Comment: ~60 % LGM-length
AR 21	Yes, the earlier reorganization in atmospheric circulation is the one that drove the Tioga 4 readvance, which culminated with glacier lengths that were ~60 % LGM glacial lengths. We'd be pleased to clarify this sentence in a revised version of the manuscript.
RC 22	Screenshot from the preprint… magnitude and more permanent reorganization that brought warmer summers and/or drier winters to the range (driving the deglaciation). This inference, derived from the Sierra Nevada's Comment: latest/final
AR 22	Yes, "driving the final deglaciation" of the range – if we ignore the subsequent (ca. 14–13 ka) Recess Peak glacial advance, which was relatively minor (Clark and Gillespie, 1997; Phillips, 2016, 2017).

RC 23	Screenshot from the preprint… 16.5 ka (Praetorius et al., 2020). Numerical modeling shows these cooler SSTs would have generated a deeper and longer lasting snowpack in the Sierra Nevada, with warmer SSTs having the opposite effect (Peteet et al., 1997). Comment: is it truly a cause-effect mechanism?
AR 23	Yes, we think oceanic conditions offshore western North America influence climate conditions onshore, such as temperature, precipitation, and snow-depth and snow-duration patterns.
RC 24	Screenshot from the preprint… The duration of the Tioga 4 deglaciation provides a maximum constraint on the duration of the second reorganization. However, the cosmogenic surface-exposure ages constraining the Comment on “Tioga 4”: this terminology must first be introduced to the generic reader who is not familiar with the Sierra glacial history
AR 24	We agree. While we initially resisted providing a full summary of Sierra Nevada glacial terminology in the Introduction – preferring to save the fuller, deeper treatment for section 2, Regional setting – we have come to realize as a result of this comment and a comment by Reviewer #2’s (RC 76) that the section on the glacial terminology of the Sierra Nevada needs to be moved into the Introduction.
RC 25	Screenshot from the preprint… The duration of the Tioga 4 deglaciation provides a maximum constraint on the duration of the second reorganization. However, the cosmogenic surface-exposure ages constraining the Comment on “deglaciation”: could you really refer to Tioga4 as a deglaciation, rather than a re-advance or stillstand during the generalised deglaciation trend of the lateglacial? If so, you should use something like "post-Tioga4 deglaciation" here.
AR 25	The Tioga 1–4 terminology was introduced by Phillips et al. (1996) to describe clusters of ^{36}Cl-dated moraine ages in three valleys on the east side of the Sierra Nevada and one valley in the adjacent White Mountains, with the “Tioga 4” grouping being the youngest and least extensive glacial advance of the four. In the strictest definition of these terms, they refer to the moraines. However, each of these moraines reflects a period of glacial growth and a subsequent period of glacial retreat, hence our usage of the terms “Tioga 4 readvance” and “Tioga 4 deglaciation.”

	We will more clearly define what we mean by these terms in a revised version of the text.
RC 26	Screenshot from the preprint… The duration of the Tioga 4 deglaciation provides a maximum constraint on the duration of the second reorganization. However, the cosmogenic surface-exposure ages constraining the Comment: is this the key research question of this paper, or one of? If so, it would be good if you could spend a few more words explaining why this matter, more generally.
AR 26	As mentioned in AR 3 and AR 12, constraining the duration of the post-Tioga 4 deglaciation is one of this manuscript's foci, but not the most important one. Please see AR 3 and AR 12 for more discussion of this topic.
RC 27	Screenshot from the preprint… of the second reorganization. However, the cosmogenic surface-exposure ages constraining the duration of this deglaciation to <500–1000 years (Phillips et al., 2009) are all associated with a Comment: phase or stadial would be better
AR 27	We agree that we should more precisely define what we mean by "the duration of deglaciation" – but we disagree that "stadial" would be a better alternative. A stadial is a period of glacial advance or of colder weather associated with a glacial advance (Foster Flint, 1971, p. 372; Andrews and Voelker, 2018). Here, we are interested in the period of glacial retreat and why the climate of the Sierra Nevada transitioned from being conducive to moderate glaciation (with glaciers at lengths equal to about 60 % their LGM lengths) to being inconducive to glaciation (with only cirque glaciers in the range, if any glaciers at all). As described in AR 25, we will more clearly define what we mean by the terms "the Tioga 4 readvance" and "the Tioga 4 deglaciation."
RC 28	Screenshot from the preprint… single former glacier – the Bishop Creek Glacier – thus permitting the possibility that glacial recession was substantially slower (or more rapid) elsewhere in the range. Comment: this
AR 28	Thank you for catching this typo; we will insert the missing word.

RC 29	Screenshot from the preprint… midMC – middle Mono Creek; and uppMC – upper Mono Creek. The other abbreviation on panel d: PB – Pioneer Basin. **(e)** 2014 aerial photo of the Lake Edison moraine complex, which was exposed by drought. **(f)** Map of Bishop Creek Canyon and vicinity. Sampling-location Comment: is this the inset in d? Also, where is f?
AR 29	Yes, any earlier version of the figure had the inset in panel (d) labeled as panel (e) and then the map of Bishop Creek Canyon (the panel in the lower right) labeled as panel (f). When we updated the figure to the current version, we forgot to update the caption. The caption is correct as written – except "(e)" should be "Inset:"
RC 30	Screenshot from the preprint… The range's length, orientation, and elevation make it an effective barrier to maritime air masses originating over the Pacific (e.g., Pandey et al., 1999). Furthermore, the range Comment: this implies a east-ward circulation, presumably present-day (what about in the past?) which you have not described
AR 30	Yes, this sentence does assume that the atmospheric circulation over the Sierra Nevada is predominantly west to east, which is the modern direction (e.g., Pandey et al., 1999), and the direction produced in numerous climate models of Ice-Age atmospheric circulation (e.g., Bartlein et al., 1998; Bromwich et al., 2004; He, 2011; Lora et al., 2016).
RC 31	Screenshot from the preprint… abundant snowfall. In Tuolumne Meadows for example (~2600 m elevation), 82% of its 1985–2017 precipitation arrived in the six months between November 1 and April 30 and 50% of that precipitation was snow (http://cdec.water.ca.gov). Average April snow depths at the elevation of Comment: how much, on average, per year?
AR 31	Annual average precipitation in Tuolumne Meadows between 1985 and 2017 was 131 cm.
RC 32	Screenshot from the preprint… 1996; Phillips et al., 2009) and then the comparatively minor Recess Peak (Birman, 1964; Clark and Gillespie, 1997). Tioga 1 predates both the local and global LGM (Phillips et al., 1996; Phillips et al., 2009); Tioga 2 marks the local LGM, which was ca. 24–21 ka (e.g., Clark et al., Comment: if this was not the local LGM, how did it get preserved during Tioga 2?

AR 32	Two Tioga 1 moraines are reported from the Sierra Nevada, one from Little McGee Canyon (Phillips et al., 1996) and one from Bishop Creek Canyon (Phillips et al., 2009). The Tioga 1 moraine in Little McGee Canyon was preserved by normal faulting and the Tioga 1 moraine in Bishop Creek Canyon was preserved by an avulsion of the glacier through its lateral moraine. Phillips et al. (2009) speculates that the avulsion was caused by meltwater running off the glacier and cutting a channel through the lateral moraine.
RC 33	Screenshot from the preprint… 2003; Phillips et al., 2009; Amos et al., 2010; Rood et al., 2011); Tioga 3 represents a readvance to ~90 % the LGM ice extent ca. 23–20 ka (e.g., Schaefer et al., 2006; Phillips et al., 2009; Stock Comment (line 156): how do we know is a readvance rather than a stillstand during retreat?
AR 33	We do not know whether the Tioga 3 moraines represent a readvance or a stillstand during retreat. Phillips et al. (1996) developed the Tioga 1–4 terminology and interpreted each of those four moraine sets as representing a glacial advance. While Phillips et al. (1996) offers no justification for interpreting the Tioga 3 moraines as a readvance versus a recessional stillstand, this interpretation has been widely accepted within the literature on the glacial history of the Sierra Nevada (e.g., Gillespie and Clark, 2011; Rood et al., 2011). Although we think a glacial readvance is more likely than a recessional stillstand – per the arguments of Anderson et al. (2014) that "interannual climate variability" (weather) can drive kilometer-scale glacial advances for glaciers with average lengths of 20 km – we will modify this sentence to read: "… Tioga 3 represents a readvance to (or recessional stillstand at) ~90 % LGM-glacier-length, with a reconstructed ELA on the eastern side of the Sierra Nevada of ~2,500–2,700 m (Phillips, 2017), at ca. 23–20 ka (e.g., Schaefer et al., 2006; Phillips et al., 2009; Stock…"
RC 34	Screenshot from the preprint… Phillips et al., 2009); Tioga 2 marks the local LGM, which was ca. 24–21 ka (e.g., Clark et al., 2003; Phillips et al., 2009; Amos et al., 2010; Rood et al., 2011); Tioga 3 represents a readvance to ~90 % the LGM ice extent ca. 23–20 ka (e.g., Schaefer et al., 2006; Phillips et al., 2009; Stock and Uhrhammer, 2010); and Tioga 4 marks a readvance to ~60 % LGM ice extent ca. 16 ka Comment (line 157): this timing overlaps with the LGM as described above..

AR 34	The Tioga 2 moraines are stratigraphically older than the Tioga 3 moraines and the Tioga 3 moraines are stratigraphically older than the Tioga 4 moraines. The age ranges we give here for the moraines – with the Tioga 2 (local LGM) dating to ca. 24-21 ka and the Tioga 3 dating to ca. 23-20 ka, for example – reflects the uncertainty in cosmogenic surface-exposure dating.
RC 35	Screenshot from the preprint… to ~90 % the LGM ice extent ca. 23–20 ka (e.g., Schaefer et al., 2006; Phillips et al., 2009; Stock and Uhrhammer, 2010); and Tioga 4 marks a readvance to ~60 % LGM ice extent ca. 16 ka (Phillips et al., 2009; Phillips, 2016). Comment: Ditto
AR 35	The argument that the "confluence moraine" at the junction of the Middle Fork of Bishop Creek Canyon with the South Fork of Bishop Creek Canyon represents a readvance and not a stillstand of the ice margin during retreat originates with (Bateman et al., 1965, p. 173-174 of the pdf). He noted the steepness of the descending lateral moraines and interpreted that they recorded a readvance, rather than a stillstand. Phillips (2017, p. 538) discusses this interpretation – that the Sierra Nevada's Tioga 4 moraines mark a readvance and not a stillstand – and notes (once again) the steepness of descent of the Tioga 4 lateral moraines. Phillips (2017) also mentions the general absence of recessional moraines behind the Tioga 4 moraines, and concludes that the Tioga 4 moraines likely represent a readvance (rather than a stillstand), while noting that it is difficult to absolutely prove that they reflect a readvance. We will revise the text to read as follows: "… and Tioga 4 marks a readvance to (or recessional stillstand at) ~60 % LGM-glacier-length, with a reconstructed ELA on the eastern side of the Sierra Nevada of ~2,900 m (Phillips, 2017), at ca. 16 ka (Phillips et al., 2009; Phillips, 2016)."
RC 36	Screenshot from the preprint… (Clark and Gillespie, 1997). This paper focuses the Tioga 4 readvance and the subsequent deglaciation. Comment: on
AR 36	Thank you for catching that typo; we will correct the sentence.

RC 37	Screenshot from the preprint… Phillips et al., 2009; Marcott et al., 2019), the innermost end moraines of the Sierra Nevada – the Tioga 4 moraines – are ~60 % the distance (15 and 22 km in Bishop Creek and Mono Creek Comment: This comment is not pertinent to this sentence in particular, but, in general, I find it odd that so much importance is given to the glacier length (or percentage of), which would naturally vary depending on several factors, and especially the hypsometry of the glacier bed. Why not using ELA instead?
AR 37	Thank you for the suggestion of using an ELA reconstruction instead of a % LGM-glacier-length reconstruction. While we will retain some mention of the Tioga 4 moraines reflecting glacier lengths that were roughly 60 % LGM-glacier lengths, to give readers a sense of the relative lengths, and because the "~60 % LGM-glacier-length" statistic is relatively common with the literature on the Tioga 4 moraines, in general we will switch the text to an ELA-based perspective.
RC 38	Screenshot from the preprint… 1995; Phillips et al., 2009). Distal of ~60 %, end moraines are common and bedrock basins are typically sediment-filled; proximal of ~60 %, bedrock basins are water-filled, bedrock-outcrop exposure is excellent, and glacial sediments are primarily isolated boulders and till patches (Clark, 1976; Clark and Clark, 1995). Comment: Is this change abrupt? Otherwise one could argue that it is a simple sediment availability issue, rather than duration Are we talking about nested Tioga 4 end moraines, or in between 3 and 4?
AR 38	Clark (1976) and Clark and Clark (1995) argue this change is abrupt. The abundant end moraines between 100 % LGM-glacier length and ~60 % LGM-glacier length include the Tioga 2, 3, and 4 moraines. The innermost end moraine in Sierra Nevada valleys is typically at ~60 % LGM-glacier length (the Tioga 4 moraines); this moraine marks the boundary between to the two sedimentary regions, with bedrock basins commonly sediment-filled distal of ~60 % LGM-glacier length and commonly water-filled proximal of ~60 % LGM-glacier length.
RC 39	Screenshot from the preprint… (24–22 km; Figs. 1d–e and 2) – till thickness systematically decreases from the outermost to innermost moraine; immediately behind the innermost moraine, till is absent for 4 km (Birman,

AR 39	Thank you for this suggestion; we will delete this word.
RC 40	Screenshot from the preprint… also consistent with rapid deglaciation. Phillips (2016) correlated the entire Lake Edison moraine complex with the Tioga 4 glacial advance and used the elevation difference between the moraines and various unspecified cirque headwalls in the Mono Creek drainage to reconstruct an equilibrium-line altitude (ELA) of 2800 m for the Tioga 4 advance. Based on Pioneer Basin's Comment: but how do we know glaciers retreated this far or disappear altogether?
AR 40	We know that Sierra Nevadan glaciers at least retreated into their cirques or *very* close to them during the deglacial phase that followed the Tioga 4 readvance because they must have been at least as small as the relatively minor Recess Peak glacial advance. The Recess Peak readvance was between ca. 14 ka and ca. 13 ka and the largest glacier in the Sierra Nevada during that readvance was approximately 4 km long (Phillips, 2017). Thus, at the end of the deglacial phase that followed the Tioga 4 readvance, the largest glacier in the Sierra Nevada cannot have been longer than 4 km. With regards to estimating the ELA responsible for the Tioga 4 readvance (as the sentence on lines 184-187 does), it doesn't matter how extensive the glacial retreat was following the readvance.
RC 41	Screenshot from the preprint… equilibrium-line altitude (ELA) of 2800 m for the Tioga 4 advance. Based on Pioneer Basin's cirque-floor elevation (~3400 m), this reconstruction implies the Tioga 4 deglaciation was driven by a ≥600 m ELA rise. This ELA rise is a minimum estimate because the climatological Comment (line 188): I think you need to be careful and very consistent with the terminology. Is Tioga 4 the name given to the re-advance? If so, best not to refer to a Tioga 4 deglaciation. Rather, you may want to say post-Tioga4 deglaciation.
AR 41	As described in AR 25, we will revise the text to clearly define our terminology. Tioga 4 is the name given to the innermost Pleistocene end moraines of the Sierra Nevada (excluding the relatively minor Recess Peak moraines; Clark and Gillespie, 1997), which are at ~60 % LGM-glacier length (Clark, 1976; Clark and Clark, 1995; Phillips et al., 2009). The Tioga 4 term was introduced by Phillips et al. (1996). The Tioga 4 moraine is inferred to represent a glacial readvance (and not a stillstand; Bateman et al., 1965; Phillips et al., 2009). We use the term "Tioga 4 readvance" to refer to the time when Sierra Nevadan glaciers had a positive mass balance and

	were expanding to what would become their Tioga 4 limits. We use the term “Tioga 4 deglaciation” to refer to the time when Sierra Nevadan glaciers had a negative mass balance and were downwasting and shrinking back from their Tioga 4 moraines. We will more clearly define these terms in a revised version of the manuscript.
RC 42	Screenshot from the preprint… by a ≥600 m ELA rise. This ELA rise is a minimum estimate because the climatological snowline may have risen above the elevation of the cirque floors. Comment: it might also be an overestimation, based on the ELA methodology applied
AR 42	While all ELA estimates are subject to random errors that might produce either an overestimate or an underestimate, we are unaware of any evidence that the toe-to-headwall altitude ratio (THAR) method of reconstructing ELAs is prone to producing overestimates. Indeed, Meierding (1982) compared six methods for reconstructing former ELAs and the THAR and the accumulation-area ratio (AAR) methods produced the lowest root mean square errors (RMSEs) of all six methods. The THAR and AAR methods produced RMSEs of approximately 80 m. The other four methods considered were the glaciation threshold, the median altitude of small reconstructed glaciers, the elevation of the lowest cirque floors, and the highest elevation of lateral moraines. These four methods all produced reconstructed ELAs with higher RMSEs than the THAR and AAR methods.
RC 43	Screenshot from the preprint… landforms – Clark (1976) and Clark and Clark (1995) interpreted that Sierra Nevadan glaciers stagnated and rapidly melted ~~at the end of the last glaciation~~. Comment: after the Tioga 4 readvance.
AR 43	Thank you for this suggested rewording. We will adopt it.
RC 44	Screenshot from the preprint… deglaciation and placed this event at 15.75 ± 0.5 ka (1 σ). This determination was based on three bulk-sediment radiocarbon dates from high-altitude ponds within the Tioga 4 glacial footprint (Fig. 1b). From north to south, and when calibrated with Calib 8.2 (Stuiver and Reimer, 1993) Comment: how much higher than the Tioga4 moraines in those valleys?

AR 44	On average, these three high-altitude ponds are about 525 m higher in elevation than the moraines for which we report new or recalculated ages. The three ponds (north to south) are at elevations of 2,625 m (Highland Lakes), 3,091 m (Greenstone Lake), and 2,864 m (East Pond) while the dated Tioga 4 moraines are at 2,330 m (Lake Edison) and 2,340 m (Bishop Creek Canyon). We will revise the sentence to read (new text in blue): "This determination was based on three bulk-sediment radiocarbon dates from high-altitude ponds (2,625–3,091 m) within the Tioga 4 glacial footprint (Fig. 1b)."
RC 45	Screenshot from the preprint… (Phillips, 2016) as the best estimate for the timing of deglaciation in the high-elevation lake basins elsewhere in the Sierra Nevada. Comment: there is of course a question of representativeness. How much evidence from a few sites can be taken to describe glacier dynamics across a whole mountain range? Could there be arguments for variability in glacier dynamics?
AR 45	First, while more minimum-limiting radiocarbon dates on the timing of the "Tioga 4 deglaciation" (the widespread deglaciation that occurred immediately after the culmination of the Tioga 4 readvance) would certainly be welcome, these three dates are the constraints that presently exist. With the radiocarbon (Clark et al., 1995, 2003; Power, 1998; Phillips, 2016) and cosmogenic surface-exposure dating (Rood et al., 2011) constraints presently available, there's no evidence for variability in glacier dynamics or for a latitudinal gradient in the timing of deglaciation in the Sierra Nevada, such as a later deglaciation in the northern Sierra Nevada than in the southern Sierra Nevada. More fundamentally – within the context of this manuscript – our goal in reviewing the radiocarbon constraints on the timing of the "Tioga 4 deglaciation" is to establish a framework for evaluating the ages reported by the three online surface-exposure age calculators. Within this context, the most relevant radiocarbon date is the 15.69 ± 0.09 ka basal date from Greenstone Lake (Clark et al., 2003), which dates the deglaciation and subsequent revegetation of a landscape that was within 4 km of the Tuolumne Glacier's accumulation zone. Ice from within 4 km of Greenstone Lake flowed across Tioga Pass and then on through Tuolumne Meadows (Wahrhaftig et al., 2019), passing 1–2 km from our sampling sites in Tuolumne Meadows. Considering the full radiocarbon-dating-uncertainty envelope for the Greenstone Lake sample, we can be 99 % confident that Greenstone Lake was both deglaciated and accumulating organic carbon by 15.4 ka. Although we cannot be completely certain that our ^{10}Be sampling sites in Tuolumne Meadows were also deglaciated by then, it seems likely – given the proximity of the Greenstone Lake radiocarbon date to our ^{10}Be sampling sites and

	the methodological fact that radiocarbon dates the revegetation of a landscape while the ^{10}Be dates the deglaciation of a landscape. As is discussed later in the manuscript, the CRONUScalc 2.0 (Marrero et al., 2016) and CREp (Martin et al., 2017) calculators produce ^{10}Be surface-exposure ages for our sampling sites in Tuolumne Meadows that are more consistent with the deglacial chronology provided by the Greenstone Lake radiocarbon date while version 3.0.2 of the Balco et al. (2008) calculator produces ages that are less consistent with the Greenstone Lake radiocarbon date. In particular, CRONUScalc 2.0 and CREp produce site-average surface-exposure ages of 16.0–15.5 ka for our Tuolumne Meadows sites while the Balco et al. (2008) calculator produces site-average surface-exposure ages of 15.2–14.7 ka. Thus, within the results provided by the Balco et al. (2008) calculator, even the oldest site-average surface-exposure age has a nominal age that is younger than the lower 99 % confidence bounds (15.4 ka) on the Greenstone Lake radiocarbon date. Thus, even if there were legitimate arguments for glacier (or atmospheric) dynamics influencing the timing of deglaciation along the ~600-km length of the Sierra Nevada, none of these arguments would alter the fact that the CRONUScalc 2.0 (Marrero et al., 2016) and CREp (Martin et al., 2017) calculators are more likely producing more accurate surface-exposure ages for the ^{10}Be samples we report in this manuscript than the "Version 3" calculator (Balco et al., 2008). Assessing the accuracy of the cosmogenic surface-exposure calculators is our driving motivation for reviewing the radiocarbon constraints on the timing of the "Tioga 4 deglaciation." All this said, we will revise the sentence to read (new text in blue): "…(Phillips, 2016) as the best available estimate for the timing of deglaciation in the high-elevation lake basins…"
RC 46	Screenshot from the preprint… 256 both the San Joaquin and Bishop Creek Glaciers. Based on these dates, Phillips et al. (2009) 257 concluded that the Tioga 4 deglaciation lasted <500–1000 years. Comment: Could 2.2 overall be reduced by about 30%? I think it is a bit too much details on stuff that has been published already and which could be summarised further.
AR 46	We are not comfortable reducing this section by as much as 30 % because it lays out essential background information on the deglaciation that followed the culmination of the Tioga 4 readvance – but we will reduce it by at least 10 %.

RC 47	Screenshot from the preprint… 3. Materials and methods Comment: could part of this be migrated to the supplementary?
AR 47	Yes.
RC 48	Screenshot from the preprint… anomalously old (ca. 22 ka) and we preemptively excluded this sample from our reanalysis. We also exclude the twenty-three bedrock ^{10}Be samples reported by Dühnforth et al. (2010) from Tuolumne Meadows and Lyell Canyon because uncertainties regarding the degree of inheritance and snow shielding. These samples were collected from small bedrock protrusions (e.g. roche moutonnées) and the heights of these protrusions were not reported. Additionally, we exclude the Comment: some of these could be rather tall, do you have their coordinates and could check on Lidar? Also given that some of your samples are only 35 cm. Would these additional ages disrupt your interpretation considerably? It sounds like a lot of potentially valuable samples to exclude, but I am sure you have good reasons
AR 48	We excluded the Dühnforth et al. (2010) samples from our reanalysis for two reasons: (1) uncertainty regarding their degree of inheritance and (2) uncertainty regarding the height of these roche moutonnées and thus uncertainty in the appropriate snow-shielding correction. While lidar coverage of these samples has become available since we first drafted this text, thus substantially reducing the uncertainty around roche moutonnée height, and thus about the snow-shielding correction factors, our concerns about inheritance in these samples remain.
RC 49	Screenshot from the preprint… *3.4. Snow-shielding correction* Snow-shielding corrections for the thirty-one new ^{10}Be samples from Yosemite National Comment: this is always a struggle but I appreciate the effort. I think it would be fair mentioning the high level of uncertainty with any such calculation, given that who knows really how much snow there was for millennia prior to the present.. How much does this correction affect your ages?
AR 49	As we acknowledge in AR 5, extrapolating snow conditions from the last ~50-100 years to the last *ca.* 16,000 years is indeed a large extrapolation (~160-320x). However, a snow correction is clearly required (see, for example, Fig. 2-5 in the

	lead author's dissertation) and extrapolating from recent snow observations to the distant past is the most commonly used approach to solving this problem. Moreover, recent snow conditions in the Sierra Nevada (*i.e.*, the last ~50-100 years) seem to be reasonably representative of average snow conditions there over the last *ca*. 16,000 years. For example, if *no* snow correction is applied to the ages, then variations in boulder height explain 27-29% of the age variations between the samples (depending on choice of calculator (Fig. 2-5 in Becker's dissertation). However, if we (1) apply a correction for seasonal snow shielding and (2) assume it is equal to historical snow conditions in the Sierra Nevada (since 1945, more or less), then boulder height only explains 0.2-0.4% of the age variation. And, unlike all other surface-exposure dating studies that we are aware that use historical snow conditions to correct for snow conditions over the postglacial interval, we propagate the modern uncertainties in snow-water equivalent (SWE) vs. elevation (Fig. S21 in the manuscript) and in average snowpack density vs. SWE (Fig. S22c) into our preferred set of cosmogenic surface-exposure age uncertainties (*i.e.*, those from the CRONUScalc 2.0 (Marrero et al., 2016) calculator). Thus, compared with most previous cosmogenic surface-exposure dating studies that use historical snow conditions to correct for snow shielding over the "post-glacial interval" (however long that might be), the approach we describe in this manuscript includes more sources of uncertainty and thus is more likely to be representative of that longer interval (the past *ca*. 16,000 years in this case) than the reported age uncertainties in those other publications. Finally, with regards to the strength of the snow-shielding correction, it varies with sample height and elevation and ranges from 0.2 % to 11.9 % for the samples we report in this manuscript.
RC 50	Screenshot from the preprint… 466 location is the bottom of Lyell Canyon (an intermediate location, but the site with the greatest ice 467 thickness). In the Version 3 results, the sample (TM14-15) from lower Tuolumne Meadows has Comment: based on?
AR 50	Wahrhaftig et al. (2019), we will add this citation to the sentence, thank you.
RC 51	Screenshot from the preprint…

	This manuscript's goal is to place the Sierra Nevada's final deglaciation in a robust regional and global context. That narrative, however, depends upon the cosmogenic dates and the Comment: is it fair to talk about the Sierra as a whole, given its size and the number of sites investigated? A statement on representativeness would be useful
AR 51	We will revise this sentence to read (new text in blue font): "…to place the central Sierra Nevada's final deglaciation…"
RC 52	Screenshot from the preprint… mean ages range ~~from~~ 16.0–15.5 ka (Table 2). For the three remaining locations, larger
AR 52	Thank you for catching this issue; we will delete the word "from".
RC 53	Screenshot from the preprint… Accordingly, with the goal of streamlining the Discussion going forward, we will henceforth exclusively refer to the CRONUScalc 2.0 ages, which are indistinguishable from the CREp ages. This interpretive decision results in the following deglacial narrative: the innermost Comment: the pages above this point, in this section, could be migrated to the supplementary.
AR 53	We will rewrite Section 5.2.2. *On the accuracy of the cosmogenic surface-exposure calculators* to read as follows: "Accepting the bulk-organic radiocarbon dates as accurate minimum limits on the timing of the Tioga 4 deglaciation suggests that the CRONUScalc and CREp dates are probably more accurate than the Version 3 calculator's dates for the ^{10}Be samples reported here. Our argument for this interpretation is provided in the online supplement (Sect. S.8.). Accordingly, with the goal of streamlining the Discussion going forward, we will henceforth exclusively refer to the CRONUScalc 2.0 ages (which are indistinguishable from the CREp ages). This interpretive decision results in the following deglacial narrative: the innermost…" <u>Note</u>: This revised Section 5.2.2. does three things: 1. it retains the opening sentence of Section 5.2.2. from the submitted manuscript, 2. it adds a new sentence referring readers to the supplement, and then 3. it moves the text in lines 736–779 of the submitted manuscript to the supplement (as suggested by the reviewer).

	Thus, we fully accept the reviewer's suggestion to move the lines above 780 in this section to the supplement, with the solo exception of the section's opening sentence. The text that is being moved to the supplement will become section S8 of the supplement – and sections S8 through S14 of the submitted supplement will become sections S9 through S15 of the revised supplement.
RC 54	Screenshot from the preprint… Figs. 3f). This narrative is consistent with geomorphic interpretations of rapid deglaciation and ice thinning in the Sierra Nevada at the end of the last glaciation (Clark, 1976; Clark and Clark, 1995) and with observations from Alaska (Cushing, 1891; Reid, 1896; Field, 1947; Mickelson, 1971; Syverson, 1995), and interpretations (Goldthwait, 1938; Lowell, 1985; Lowell et al., 1990) and dating (Bierman et al., 2015; Davis et al., 2015; Koester et al., 2017, 2021; Corbett et al., 2019; Drebber et al., 2023; Halsted et al., 2024) from New England and adjacent regions (Barth et al., 2019) for how rapid deglaciation proceeds in mountainous landscapes (Goldthwait and Mickelson, 1982). Comment: in general or for this specific time interval? I would be careful with generalisations such as this one
AR 54	This is a general statement about how deglaciation proceeds in a mountainous landscape when the ELA rapidly rises to such a height that only cirque glaciers (if that) can be sustained and follows the work of those cited above, especially the summarizing work of Goldthwait and Mickelson (1982). While we agree that care is required when making general statements, this is a general statement that is well supported by the literature (i.e., the citations in these lines of the preprint). <u>We will clarify this sentence by modifying it to read as follows</u>: "This narrative is consistent with geomorphic interpretations of rapid deglaciation and ice thinning in the Sierra Nevada at the end of the last glaciation (Clark, 1976; Clark and Clark, 1995) and with observations from Alaska (Cushing, 1891; Reid, 1896; Field, 1947; Mickelson, 1971; Syverson, 1995), and interpretations (Goldthwait, 1938; Lowell, 1985; Lowell et al., 1990) and dating (Bierman et al., 2015; Davis et al., 2015; Koester et al., 2017, 2021; Corbett et al., 2019; Drebber et al., 2023; Halsted et al., 2024) from New England and adjacent regions (Barth et al., 2019) for how deglaciation proceeds in a mountainous landscapes when the ELA rapidly rises and glaciers become disconnected from their accumulation zones (Goldthwait and Mickelson, 1982; Vacco et al., 2010)."
RC 55	Screenshot from the preprint…

the central Sierra Nevada from innermost moraine stabilization to the melting of the last remanent ice masses is 1.0 kyr, with a 95 % confidence range of 0.2–3.0 kyr (Fig. 7c).

Comment:
how fast is this, really? Perhaps the narrative should focus on putting this in relative terms. Faster than (what occurred between Tioga 3 and 4? or Tioga 2 and 3? Or elsewhere in similar settings for this same time period? etc.), rather than just fast or abrupt.

How much topography and elevation was available above the Tioga 4 moraines?

And finally, would it be possible to estimate a retreat rate? For many this parameter would be easy to put into context, as present-day glaciologists often talk in terms of retreat rates

AR 55

The reviewer raises five to six questions in this comment:

How fast, really, is a ca. 1.0 kyr deglaciation?

1. It was fast within the context of geomorphology. Meaning, there is no record of episodic ice advances or stillstands after the Tioga 4 retreat started at ca. 16.4 ka. The Tioga 4 moraine is the innermost end moraine in the Sierra Nevada. Before then, interannual climate variability (weather) and/or genuine climate change was able to shift the glaciers of the Sierra Nevada into positive mass balance and driven them forward to generate a moraine record. After the start of the Tioga 4 deglaciation at ca. 16.4 ka, there is no geomorphic record of that happening.

How fast was the "Tioga 4 deglaciation" compared with the ice retreat between the Tioga 2 and Tioga 3 ice advances?

2. Quantitatively comparing the rate of ice retreat following the Tioga 4 with the rate of ice retreat between the Tioga 2 (LGM) glacial advance and the Tioga 3 readvance is challenging because we don't know how far glaciers receded during that interval, only that the minimum glacier extent in the Sierra Nevada between the Tioga 2 and Tioga 3 glacial advances must have been <90 % LGM-glacier length because the Tioga 3 readvance reached ~90 % LGM-glacier length.

How fast was the "Tioga 4 deglaciation" compared with the ice retreat between the Tioga 3 and Tioga 4 ice advances?

3. Likewise, quantitatively comparing the rate of ice retreat during the "Tioga 4 deglaciation" with the rate of ice retreat between the Tioga 3 and Tioga 4 readvances is also hard because we don't know how far back the ice shrank

during this interval, only that it retreated from ~90 % LGM-glacier length to less than about 60 % LGM-glacier length.

How fast was the "Tioga 4 deglaciation" compared with ice retreat rates elsewhere on the planet in mountainous settings at ca. 16 ka?

4. In Tuolumne Meadows and Lyell Canyon, the ice margin melted back at an average rate of 20 m yr^{-1} from the lower Tuolumne Meadows sampling site to the bottom of Lyell Canyon sampling site.

   In Mono Creek Canyon, the ice margin melted back at an average rate of 13 m yr^{-1} from the innermost Lake Edison moraine to the lower Mono Canyon Creek sample and then at an average rate of 31 m yr^{-1} from there to the cirques in Pioneer Basin, which is consistent with a downwasting ice mass that is becoming more out of equilibrium with climate as it shrinks. These retreat rates roughly cover the ca. 16.4 ka to ca. 15.6 ka intervals.

   In comparison, in the Front Range of Colorado, Dühnforth and Anderson (2011) report ages and sampling positions from Green Lakes Valley that produce an average retreat rate of 0.8 m yr^{-1} over the *much* longer interval from ca. 24 ka to ca. 12 ka; in the Upper Arkansas River basin of Colorado, Young et al. (2011) report ages and sampling positions that produce an average retreat rate of 1.7 m yr^{-1} over the ca. 19 ka to ca. 14 ka interval; also in the Upper Arkansas River basin of Colorado, Schweinsberg et al. (2020) report ages and sampling positions that indicate the average ice-margin retreat rate between ca. 20.6 ka and ca. 15.6 ka was 1.1 m yr^{-1} and then was 17 m yr^{-1} between ca. 15.6 ka and ca. 14.1 ka.

   In contrast, ice-marginal recession rates along the southern and southeastern margin of the Laurentide Ice Sheet were faster than those we document in the central Sierra Nevada. Lowell et al. (2021) documented near-constant retreat rates of between ~40 m yr^{-1} and ~60 m yr^{-1} over the ca. 19 ka to ca. 10 ka interval along a 500-km-long SW-NE transect to the west of Lake Superior. Ridge et al. (2012) documented retreat rates of ~50-100 m yr^{-1} (18.2–17.4 ka), ~30-40 m yr^{-1} (17.4–16.2 ka), ~80–90 m yr^{-1} (16.0–14.8 ka), and ~300 m yr^{-1} (14.8–14.2 ka).

   In summary, the ice-marginal recession rates in the Sierra Nevada during the ca. 16 ka to ca. 15 ka "Tioga 4 deglaciation" were relatively fast compared with other ice-marginal retreat rates in the U.S. West over that interval and generally slower than LIS ice-margin retreat rates.

   As mentioned in AR 7, we will add the average rate of ice-margin recession in Tuolumne Meadows and Lyell Canyon (20 m yr^{-1}) and Mono Creek Canyon (first 13 m yr^{-1}, then 31 m yr^{-1}) to the manuscript. We will also

	briefly compare these rates with rates of ice margin recession elsewhere in the American West at this time. **How much topography and elevation was available above the Tioga 4 moraines?** 5. The Tioga 4 moraine in Lake Edison is 1000 m below the cirque floors in Pioneer Basin and the Tioga 4 moraine in the Middle Fork of Bishop Creek Canyon is also 1000 m below Piute Pass, which is the connection between Humphreys Basin and the North Fork of Bishop Creek Canyon. During the Tioga 4 glacial stage (and during the earlier LGM (Tioga 2) and Tioga 3 stages), ice flowed from Humphreys Basin down the North Fork of Bishop Creek Canyon and into the Middle Fork of Bishop Creek Canyon. **How many meters / year were the Tioga 4 glaciers retreating during their deglaciation?** 6. Please see our answer to question #4 above.
RC 56	Screenshot from the preprint… final deglaciation was a geomorphically abrupt event. For instance, the bottom of Lyell Canyon sampling location has the youngest mean surface-exposure age across all the sampling locations reported here (Fig. 3c; Table 2) – and a trimline-based ice-thickness reconstruction (Wahrhaftig et al., 2019) indicates the bottom of Lyell Canyon hosted an ice thickness greater than any other location we sampled. Tioga 4 ice thicknesses over the bottom of Lyell Canyon sampling site Comment: For Tioga4? With chronological constraints?
AR 56	For the LGM (Tioga 2), with the chronological constraint being derived from the large relative-age difference between the landforms of the last glaciation (MIS 2) and the landforms of the penultimate glaciation (MIS 6). Given a typical profile of ice-thickness with distance from the ice margin (e.g., Anderson and Anderson, 2010, Fig. 8.25), the bottom of Lyell Canyon would also have had the thickest Tioga 4 ice.
RC 57	Screenshot from the preprint… organic accumulation in Greenstone Lake. The observation that the locations with the thickest ice were the last to deglaciate, regardless of their distance from the cirque headwalls, indicates that the deglaciation was driven by a relatively sudden and large rise in the ELA. Comment: I am not sure I follow this argument. What would the alternative option be?

AR 57	The alternative is a slow rise in the ELA which enables the glaciers of the central Sierra Nevada to wax and wane as they generally retreat, leaving a rich end-moraine record behind that terminates in the cirques. Although the youngest Pleistocene moraines are in the cirques or just beyond them (the Recess Peak moraines), there are no known end moraines in the Sierra Nevada between the Tioga 4 moraines and the Recess Peak moraines, suggest a large and rapid rise in the ELA over at the start of that time interval (i.e., just after the culmination of the Tioga 4 readvance).
RC 58	Screenshot from the preprint… https://doi.org/10.5194/egusphere-2025-1370 Preprint. Discussion started: 3 April 2025 © Author(s) 2025. CC BY 4.0 License. Comment: weren't these described earlier? If so, avoid repetition
AR 58	This comment was apparently misapplied to the manuscript's header information. Our assumption is that reviewer #1 intended to apply it to the following passage instead (highlighted in yellow by us): 867 wintertime drying of ≥35 %, or some combination thereof. The temperature-change 868 reconstruction is based on the interpretation that the deglaciation was driven by ≥600 m rise in 51 https://doi.org/10.5194/egusphere-2025-1370 Preprint. Discussion started: 3 April 2025 © Author(s) 2025. CC BY 4.0 License. EGUsphere Preprint repository 869 the ELA (as reviewed in Sect. 2.2.1.) and the observation that modern surface-temperature lapse If we're correct in thinking that Reviewer #1 intended to highlight what we've highlighted in yellow, then our response is as follows: • No, we have not previously described our methods for converting the ELA rise into estimates of the temperature change or precipitation change

	responsible for it and – as it happens – Reviewer #2 asked for more information about these methods (RC 88). • Previously, in section 2.2.1, we describe how Phillips (2016) reconstructed the ELA responsible for the Tioga 4 readvance (1 sentence) and how much the ELA must have risen immediately following the Tioga 4 readvance in order to essentially deglaciate the central Sierra Nevada (1 sentence). • In light of RC 88 (by Reviewer #2), this section will be rewritten as described in AR 88.
RC 59	Screenshot from the preprint… with the estimated lapse rate suggests the Sierra Nevada's final deglaciation was driven by a summertime warming of ≥2 °C, assuming no change in winter precipitation (Leonard et al., 2023). Comment: the problem with attempting to define end terms with two variables is that we do not know if both changed in the same direction, glacier mass balance wise, or not. Do other proxies tell us that P decreased during this time interval? I guess this might come in the next section
AR 59	Defining limiting, end-member changes in temperature and precipitation does assume that the other variable did not change in such a way as to require a larger change in the variable in question. For example, if winter snowfall increased during the "Tioga 4 deglaciation" (i.e., during the deglaciation that followed the culmination of the Tioga 4 readvance) then a larger summer-temperature rise would be required to deglaciation the range. However, because we only know that the ELA rise responsible for the deglaciation was *at least* 600 m, we already know the temperature rise was *at least* 2 °C, even if we assume precipitation also increased (rather than remaining constant). For clarity, we will revise the sentence on lines 873–876 to read as follows (with new text in blue): "Combining the ELA change (≥600 m) with the estimated lapse rate (3–4 °C km^{-1}) suggests the central Sierra Nevada's final deglaciation was driven by a summertime warming of ≥2 °C, assuming no decrease in winter precipitation.
RC 60	Screenshot from the preprint…

	Otto-Bliesner et al., 2006; Wong et al., 2016; Jones et al., 2018). Also, as the LIS thins, it becomes a less formidable obstacle to atmospheric circulation, which enables the polar jet stream – formerly split by the LIS (Fig. 9a), with a weaker branch passing to the north of the ice sheet and a stronger branch passing to the south (Kutzbach and Wright Jr, 1985; Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986; Bromwich et al., 2004; Löfverström et al., 2014; Lora et al., 2016; Wang et al., 2024) – to reunify (Fig. 9b). We interpret that these changes in the Aleutian Comment: this aspect is pretty central in your narration of events, but I am unclear what evidence you have to justify it. Is it really necessary to explain your results? Is it one of many hypotheses? Could it be tested at all, or is it just a guess?
AR 60	Generations of numerical models of varying levels of complexity have reproduced a split-polar jet stream over North America during the LGM as a result of the LIS, as cited in this sentence, with the polar jet reunifying and shifting northward, away from the Sierra Nevada, in response to LIS thinning. Thus, it is reasonable to look for evidence of that atmospheric transformation in the landscape of the Sierra Nevada. That said, it is not necessary to explain our results and there other hypotheses, with a principal alternative being that it was the subtropical jet stream – not the polar jet stream – that brought moisture to the Sierra Nevada during the last glaciation and that its northward shift during the last glaciation was driven by changes in sea-ice extent in the North Atlantic (Chiang and Bitz, 2005; Chiang et al., 2014; Phillips, 2017; McGee et al., 2018). Distinguishing which jet stream was most responsible for moisture delivery to the Sierra Nevada during the last glaciation and deglaciation is a challenge, and cannot be unequivocally answered by the range's glacial deposits.
RC 61	Screenshot from the preprint… In summary, we infer Heinrich Event 1 sufficiently thinned the LIS at ca. 16.2 ka to trigger an atmospheric reorganization (Fig. 9). That atmospheric reorganization brought drier Comment (line 1029): wouldn't this paragraph best fit in the conclusions?
AR 61	Yes, we agree and will make the change.
RC 62	Screenshot from the preprint…

	trigger an atmospheric reorganization (Fig. 9). That atmospheric reorganization brought drier winters and warmer summers to what is now the southwestern United States. In response, the Comment: if this is based on the proxies described above, I believe you cannot really infer a seasonality of the climatic signals.
AR 62	This sentence in the preprint is poorly written. We are inferring these possible changes from the deglaciation of the central Sierra Nevada. Our argument that (a) winters were drier, or (b) summers were warmer, or (c) winters were drier *and* summers were warmer comes from the sensitivity of glaciers to winter precipitation and summer temperatures (e.g., Oerlemans, 2005). Glaciers are relatively insensitive to summer precipitation changes and winter temperature changes. Thus, the glacial geomorphic record provides little-to-no insight into how summer precipitation and winter temperatures might have changed.
RC 63	Screenshot from the preprint… winters and warmer summers to what is now the southwestern United States. In response, the central and southern Sierra Nevada essentially deglaciated and formerly expansive lakes in California, Arizona, New Mexico, and Utah desiccated (McGee et al., 2018). Offshore western Comment: non glacier fed
AR 63	We will move the paragraph on lines 1029–1038 of the preprint to the conclusions (as suggested in RC 61) and revise it to read as follows (new text in blue): "In summary, we infer Heinrich Event 1 sufficiently thinned the LIS at ca. 16.2 ka to trigger an atmospheric reorganization (Fig. 9). Based on the sensitivity of glaciers to winter precipitation and summer temperatures (e.g., Oerlemans, 2005), we infer that this reorganization brought drier winters, warmer summers, or both to what is now the southwestern United States. The central Sierra Nevada essentially deglaciated in response to this change, and formerly expansive lakes in California, Arizona, New Mexico, and Utah abandoned high-level shorelines (Waters, 1989; Allen and Anderson, 2000; Bacon et al., 2006; Munroe and Laabs, 2013; McGee et al., 2018). Numerical modeling indicates LIS thinning weakens the Aleutian Low (e.g., Otto-Bliesner et al., 2006; Yanase and Abe-Ouchi, 2010), and we infer weakening of the Aleutian Low reduced the influx of polar water into the Santa Barbara Basin, causing SSTs there to warm (Hendy and Kennett, 2000; Hendy et al., 2002; Hendy, 2010). Likewise, a concomitant northward migration of the northeastern Pacific's subtropical high reoriented winds over the Gulf of California

	and greatly reduced upwelling there, allowing subtropical water to enter the Gulf and warm SSTs there (Ganeshram and Pedersen, 1998; McClymont et al., 2012)."

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