

Reply to reviewer 2

-Reviewer 2 minor comment 1:

Line21: “suggest commas on either side of this clause”

Author reply: Change made accordingly

-Reviewer 2 minor comment 2:

Line86: “Here and in a few other locations, the reference is doing a lot of work. It would be helpful if you provided a bit more detail about the example(s) you're citing, so the reader doesn't need to be familiar with the literature to follow your point.”

Author reply: Thank you for this comment. We have now added more detail following this reference as well as for our next mention of the cultural heritage implications. This section of the introduction now features more tangible examples to help the reader better understand what we mean exactly:

“Quantifying glacial sediment routing and export in formerly glaciated landscapes is also crucial to inform industries such as concerned with aggregate resources or the geological disposal of nuclear waste (e.g. Fischer et al., 2015; 2021). Indeed, quantifying past long-term glacial sediment export and deposition dynamics helps better project future geological stability and future glaciations' impacts on possible industrial repository sites via basal erosion, ensuring safe containment of anthropogenic waste over millennia. Lastly, tracking the transport history of iconic glacial erratics, some of which have cultural significance (Reynard, 2004; Coutterand, 2018), offers an opportunity to bridge scientific understanding with public engagement. The permanent glacial erratics exhibition of Grenchen (Solothurn, Switzerland) displaying erratics found during construction works, is a prime example of a cultural connection to the paleo-glacial heritage. Thus, while it represents a substantial challenge, characterizing the pre-depositional history of glacial sediments and ice-contact deposits yields widespread implications for numerous research fields and industrial/societal activities.”

-Reviewer 2 minor comment 3:

Line95: “same point as earlier with nuclear waste, provide a bit more detail, so the reader does need to track down every reference to understand your examples.

The references should be there so they can follow up if they want additional information.”

Author reply: We have now added a more specific example to this sentence to make it clearer to the reader what was meant by “empirical data”. This goes in line with a similar comment by Reviewer 1 on this same sentence:

“Numerical modelling offers a means to address the above knowledge gaps by generating spatially distributed, time-evolving estimates of glacial sediment transport which can be compared against empirical data such as glacial erratic mapping and ice-contact sediment provenance analyses (e.g. Veness et al., 2025).”

-Reviewer 2 minor comment 4:

Line96: “Defining this for a non-modeling audience would be helpful.”

Author reply: We agree and have now added an extra sentence just following this initial statement which acts as a definition for non-modellers: “A robust and established method consists in coupling a glacier evolution model with Lagrangian particle tracking to simulate the time-transient advection of sediment-like particles by ice-flow (e.g. Rybak & Huybrechts, 2003; Rowan et al., 2015; Bernard et al., 2020; Scherler & Egholm, 2020). In a Lagrangian approach, calculations are

performed on individual moving particles themselves rather than at fixed grid locations, allowing to track their paths through the evolving glacier at sub-grid scales.”

-Reviewer 2 minor comment 5:

Line102: *“this sentence feels overly specific (specific number of particles, number of years, specific ice mass).*

It reduces the importance of the statement. If you need to be this specific, is it worth saying this?”

Author reply: Thank you for this comment: we have now simplified this sentence and removed some of its redundant components to make it also feel less specific : *“However, no studies have yet tracked large particle numbers (>106) within model simulations of past Alpine Ice Field (AIF) glaciations.”*

-Reviewer 2 minor comment 6:

Line166: *“This is stated quite a few times in the intro. I think once is fine, because it is a good study. But I'd delete the other mentions until you get to the conclusions.”*

Author reply: Thank you for this comment. We have just removed a few instances of the term “for the first time” or “the first...” describing the novel aspect of our reconstruction. As such, it now only appears once in the Abstract, once in the Introduction, and once in the Conclusion.

-Reviewer 2 minor comment 7:

Line180: *“This feels like a conclusion paragraph, highlighting results and findings. I can see the value in noting the Zenodo repository, but the rest is out of place in the intro.”*

Author reply: We agree and have now moved this paragraph out of the introduction and moved it to the beginning of the discussion: please refer to our reply to Reviewer 1 minor comment 33 on this same topic. We now also removed a few other sentences from the previous paragraph of the introduction to make the introduction less of a summary of our study: but instead with more focus on the context and motivations for our study.

-Reviewer 2 minor comment 8:

Figure 3: *“Consider removing the maximum extent between polygons, it's quite hard to see at this resolution. adding a polygon or mask for water would be helpful for readers who aren't familiar with the topography of the alps. suggest cleaning these names up, remove unnessecary_ and text. Possibly increase the size?”*

Author reply: Similar comments were also raised by reviewer 1 on Figure 3 (see our reply to Reviewer 1 minor comment 17). We have now modified the figure: removing the maximum extent outline, added country outlines with country labels for people not familiar with the alps, and added the Mediterranean sea mask (but we prefer not to include the lakes: in order to avoid confusion with our coloured sink and source polygons). We also cleaned up the names of the legend and made the text bigger for increased readability.

-Reviewer 2 minor comment 9:

Line 453: *“I don't think you need to define the acronyms here, they aren't used again in the figure caption.”*

Author reply: Change made accordingly.

-Reviewer 2 minor comment 10:

Line 599: *“I think high elevation terrain (or possibly mountains) would be better than high topographies”*

Author reply: We agree and replaced “high topographies” by “high elevation terrain” accordingly.

-Reviewer 2 minor comment 11:

Figure 5: *“The dark line disappears into the dark shading where the model oversteps the LGM extent. Maybe a bright blue outline? consider the color ramp used, this is hard to differentiate much variability (maybe there isn't much), with perhaps the exception in the SE.”*

Author reply: We agree and have now modified the colormap (although the data itself makes it challenging). Please see our reply to Reviewer 1 minor comment 24 for more details. The visibility of the LGM outline is also improved as a result of this new colormap, and we also increased its linewidth to increase its visibility.

-Reviewer 2 minor comment 12:

Line 682: *“would this just make sense presented as a range?*

It seems to suggest particles spend negative years in the glacier?”

Author reply: We agree and have now modified the reporting of these numbers across the paper using the median and the IQR in a following bracket instead. Please refer to our reply to reviewer 1 minor comment 26 for more detail.

-Reviewer 2 minor comment 13:

Line 688: *“I think you would put km here as well”*

Author reply: Change made accordingly.

-Reviewer 2 minor comment 14:

Line 691: *“Are there other time-periods where the subglacial particles are deposited and then re-entrained (though not in an ice free position)?*

I'm mostly curious what percentage of time is being transported vs stationary.”

Author reply: Thank you for this comment. We agree this is likely a potent mechanism in reality; however we do not have such a complex process modelled in our setup here. This would involve including in our modelling a parameterisation scheme for the deposition, storage, and freeze-on processes of subglacial sediments at the ice-bed interface. Here with the model results we have; we unfortunately cannot quantify this and answer your question. In our discussion section about the limitations of our study: we do however mention these existing complex processes which can make sediment transport velocity < ice velocity through storage for instance, a series of processes which represent an extra complexity which is here not taken into account in this work.

-Reviewer 2 minor comment 15:

Line 770: *“suggest: When averaging across all of the sinks”*

Author reply: Change made accordingly.

-Reviewer 2 minor comment 16:

Line 771: *“It's not very clear what this comparison is to (what is the increase on?)”*

Author reply: We agree and have now made this sentence more explicit: *“When averaging across all of the sinks, the glacial transport time for particles of supraglacial origin is higher than for those of subglacial origin by approximately 1,925 years, i.e. a factor of 1.9 increase.”*

-Reviewer 2 minor comment 17:

Line 864: *“One thing you could consider:*

Could the erratics have complex transport histories that involve multiple glacial cycles (or glacial and non-glacial transport?

I know your model doesn't examine that, but you might offer it as a possibility, given your model does not recreate the empirical hypothesis during one glaciation.”

Author reply: Yes this is a very good point. This belongs to our discussion on the limitation of our study and the likely underestimation that results from it due to the complexity of real-world glacial sediment transport trajectory diversity. We had already made a small hint at this in the original

discussion, but we have now made it more explicit in this sentence, based on this reviewer comment:

“Finally, while our GPU-based approach enables us to track an unprecedented number of particles in ice (~20.5 million) given our simulations’ spatio-temporal scales, sediments are ubiquitous in real glaciers. Moreover, our modelling also does not include the re-mobilization by glaciers and glaciofluvial systems of pre-LGM sediment deposits over multiple glacial cycles. We thus likely still underestimate the diversity of pathways glacial sediments may follow within a glacier system as complex as the former AIF during Late-Quaternary glaciations.”

-Reviewer 2 minor comment 18:

Figure 9: *“Similar to earlier comment, these maps are great, but could use water polygons, or maybe place names or borders?*

Something to help people place themselves.”

Author reply: Thank you for this comment. This also echoes comments from Reviewer 1. We have now added famous city names to panel A to help the viewer better locate these maps and data. We however try not to overload the maps with too much detail in order to not make the trajectories less visible.

-Reviewer 2 minor comment 19:

Line 1087: *“can you be more specific here?*

are there notable exceptions where/when it is not warm based”

Author reply: Thank you for your comment and for spotting this. This sentence was indeed misleading, as after double-checking, there is no need for the “nearly” statement: as virtually all of the transfluences detected via our particle trajectory analysis (e.g. Figure 10 and other maps in supplements) occur in places with modelled warm-based ice conditions, when they occur. There are no notable exceptions when it is not warm based. We have now updated the sentence accordingly.

-Reviewer 2 minor comment 20:

Line 1090: *“can you give an example here, as you did with the longer option?”*

Author reply: Yes indeed thank you for this comment. We have now added the example of the well-documented “Simplon pass” transfluence in bracket next to the short-time-span case.

-Reviewer 2 minor comment 21:

Figure 10: *“The pink letters are very hard to read on the shaded relief background. Maybe letters or symbols within a solid colour”*

Author reply: Thank you for spotting this. We have now replaced these by bigger letters in red with a thin black outline and a transparent white background underlying it: which we believe makes it easier to visualize now. The panels on this figure have now also increased in size, with less white space around them. The yellow dots for the transfluences were also made bigger.

-Reviewer 2 minor comment 22:

Line 1146: *“Does test 1 use the same number of particles as the other runs?”*

Author reply: Thank you for pointing this out. No in fact Test 1, due to the nature of the simpler seeding scheme employed, does not produce as much particles in the system as the original complex seeding scheme: with around 2 million particles at maximum. We’ve now added this information to the paragraph describing this scheme : *“The first sensitivity test uses a ‘simple’ seeding scheme, which is not process-based and instead creates particles supraglacially in a spatially- and temporally-regular manner, i.e. with seeding occurring in 20% of grid cells exclusive*

to the accumulation zone, and regularly every 300 yrs. This simpler scheme also produces less particles (~2.1 million at maximum) than the original seeding scheme.”

-Reviewer 2 minor comment 23:

Line 1160: *“I had a hard time following this, I’d make this all one sentence, as I paused at the end of the first, then went back and tried to read it again, and missed the context that came next.”*

Author reply: Thank you for this comment. To make this sentence easier to read, we have now removed the “using our source-to-sink analysis” clause which was not necessary, and have merged the two sentences together: *“In the first sensitivity test, which uses ‘simple’ seeding instead, model agreement with the locations of dated erratics presented above (section 3.4.2) decreases from 81-68% to 74-58%, with these two ranges representing whether we tolerate the small (<4 km) increase in ice extent mentioned above (section 3.4.2).”*

-Reviewer 2 minor comment 24:

Line 1178: *“A bit of a broader comment, the information in the discussion is good, though a challenge to follow in places, and especially hard to return to, as it’s a single section. A few subheadings would help give 4.1 some structure, and make it easier for the reader to refer back to something.”*

Author reply: Thank you for this comment. We have now added sub-section titles to section 4.1 to make it clearer to follow and give it more structure:

4 Discussion

4.1 Applications, limitations and future work

4.2.1 *Simplified glacial sediment transport dynamics*

4.2.2 *Simplified erosion and particle-seeding dynamics*

4.2.3 *Underestimated diversity of glacial sediment trajectories*

4.2.4 *Simplified mapping of terminal ice-contact deposits*

-Reviewer 2 minor comment 25:

Line 1246: *“computationally cheaper? or economically cheaper? I guess it could mean both, but you might clarify here.”*

Author reply: Thank you for spotting this. Here we meant computationally cheaper. To make this clearer: we have now rephrased to : *“However, as shown with this work, GPU-computing enables to lower the computational cost of coupled glacier-particle modelling by several orders of magnitude.”*