Reply to reviewer 1

-Reviewer 1 minor comment 1:
Line16: "reduction? Not quite sure what's meant by buffering here."
Author reply: Replacement made accordingly

-Reviewer 1 minor comment 2:
Line21: "Not sure you need this sub clause - I think the point is already clear."
Author reply: Agreed, we removed this sub-clause from the abstract.

-Reviewer 1 minor comment 3:
Line 67: "longer?"
Author reply: Agreed, this term was added.

-Reviewer 1 minor comment 4:
Line 69: "I'd remove yet"
Author reply: Agreed, this was removed.

-Reviewer 1 minor comment 5:
Line 74: "Perhaps because I mainly do contemporary glaciers, I'm not familiar with the exact meaning of these terms, so please could you briefly define / explain?"
Author reply: Agreed, we simplified the sentence to: *"They also inform mechanisms and timescales of debris cover and subglacial sediment storage, which can be involved in protecting bedrock from subglacial erosion (Delaney & Anderson, 2022)."*

-Reviewer 1 minor comment 6:
Line 84: "I'd swap for instance for such as."
Author reply: Agreed, this swap was made accordingly.

-Reviewer 1 minor comment 7:
Line 86: *"Interesting application. Consider adding an example here - I've never heard of it but it sparked my interest!"*
Author reply: Many thanks for the suggestion. We have now added this example to the paragraph: "*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."*

-Reviewer 1 minor comment 8:
Line 94: *"Please add a couple of examples of what this empirical data might look like"*
Author reply: We now added these examples to the 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 provenance analyses (e.g. Veness et al., 2025)."*

-Reviewer 1 minor comment 9:
Line 102: *"I'd make it clear here that you mean past limits, presumably from things like trim lines? As opposed to modern data ice thickness?"*
Author reply: Many thanks for this suggestion. Indeed we are referring to trimline data here: we have now added more detail and example references to the sentence to make this clearer: "*First,*

previous AIF simulations (e.g. Mey et al., 2016; Seguinot et al., 2018; Jouvet et al., 2023) exhibited potent mismatches in ice thickness compared to trimline elevation field data (e.g. Kelly et al., 2004; Hippe et al., 2014), limiting confidence in inferred ice-flow dynamics."

-Reviewer 1 minor comment 10:
Line 104: *"Somewhere it would be useful to give the processing time using standard approaches versus IGM, just to really bring home the difference"*
Author reply: We fully agree; and this is something we do in results section 3.1: where we provide the numbers from our quantitative test experiment comparing particle tracking on GPU vs standard methods on CPU.

-Reviewer 1 minor comment 11:
Line 159: *"enabling the coupling of the advection of....."*
Author reply: The sentence was changed accordingly.

-Reviewer 1 minor comment 12:
Line 178: *"under> in"*
Author reply: Change made accordingly.

-Reviewer 1 minor comment 13:
Line 183: "*Quite a bit of this paragraph and particularly the highlighted sentences read a bit like what I'd expect in teh final prapgraph of the discussion, where you think about broader implications / applications. Please consider whether they are better placed there."*
Author reply: Thank you for this comment, we agree and have now moved this paragraph to the beginning of the discussion instead, please alse refer to our more detailed reply to comment 33.

-Reviewer 1 minor comment 14:
Line 209: *"As a form of mass input? Perhaps worth stating."*
Author reply: Actually, as a form of mass re-distribution (from steep to less steep glacier surfaces). To make this clearer, we updated the sentence to: "*Their model setup (and thus also ours) integrates modules for ice-enthalpy (after Aschwanden et al., 2012), surface mass balance (after Calov & Greve, 2005), isostatic adjustment (after Wickert, 2015), and avalanching for mass re-distribution down steep slopes."*

-Reviewer 1 minor comment 15:
Line 402: "consists in > involves"
Author reply: Change made accordingly.

-Reviewer 1 minor comment 16:
Line 411: *"ensures that we isolate..."*
Author reply: Change made accordingly.

-Reviewer 1 minor comment 17:
Figure3: "*Is the legend required here or could the numebrs and names be in a table in the sup info? If the names are used, I'd tudy them up in the legend, e.g. remove the underscores and LGM margins, as this appears on all of them - this would help readbaility."*
Author reply: We have now redesigned the legend of Figure 3 in both panels to make it more readible (removing underscores and increasing the size of text).

-Reviewer 1 minor comment 18:
Figure3: *"Same point about the names here - the text is so small it's hard to read, so think about simplifying / shortening the names or just going with the numbers"*

Author reply: We have now redesigned the legend of Figure 3 in both panels to make it more readible (removing underscores and increasing the size of text).

-Reviewer 1 minor comment 19:
Line 490: *"consists in > involves"*
Author reply: Change made accordingly.

-Reviewer 1 minor comment 20:
Line 502: *"software"*
Author reply: Change made accordingly.

-Reviewer 1 minor comment 21:
Line 511: *"which is"*
Author reply: Change made accordingly.

-Reviewer 1 minor comment 22:
Line 517: *"Quite a few times you say small computational cost - it'd be good to put some numbers to this to give the reader a sense. E.G. it takes x minutes instead of xxxxx hours.*
OK, reading on you do this in the next paragraph, but woudl be worth adding to the abstract ./ intro."
Author reply: To address this we have now added an extra sentence in the abstract to mention an estimate of the speed-up we observe:

"*Our approach unlocks the ice advection of tens of millions of particles at minimal additional computational cost, allowing simulations of glacial sediment transport across the European Alps over multi-millennial timescales (40-18 ka) and at an unprecedented spatial resolution of 300 m. We achieve ~50x faster computation tracking 20 million particles across the Alps using a single GPU instead of 60 CPU threads. In doing so, we produce the first Alps-wide modelling reconstruction of glacial sediment transport during the LGM*"

For this specific metric we extract from our resulting analysis on CPU vs GPU costs the case of 20 million particles in the system, and 60 CPU threads vs 1GPU: which results in a x50 speed up (see figure 4). However please note that depending on what computational system people use the speed up factor can be very different. Here we choose to mention the x50 figure as a conservative estimate but actually it is quite difficult to talk about this speedup using only a single number. Moreover, as these numbers are obtained from us conducting a separate analysis and simulation testing both GPU and CPU cases, it is therefore presented as a distinct "results" section in our paper. Therefore whilst we agree it makes sense to include a summary metric in the abstract: we think it would feel out of place in the introduction. We however have now made it clearer in the relevant introduction paragraph that a quantification of this is "coming" later in in the paper :

"*Here we show that IGM's novel GPU-based architecture also enables efficient parallelization of Lagrangian particle tracking, enabling the coupling of the advection of millions of particles within our AIF model framework at minimal additional cost (see Results section for quantifications) and consequently track the glacial-transport trajectories of individual particles from their location of origin (the source) to their final deposition site (the sink).*"

-Reviewer 1 minor comment 23:
Line 590: *"cover"*
Author reply: Change made accordingly.

-Reviewer 1 minor comment 24:

Figure 5: "*I'd consider a colour map with more colours, e.g. rainbow. I'm suggesting this because it's hard to see anything but dark blue in b here.*"

Author reply: We thank the reviewer for this comment. Please note that this is here also caused by the nature of the density data in panel B characterised by the majority of hexagons featuring few particle seeding point numbers (with high density points being quite rare and with a lot of noise in panel B), which makes it quite hard (we've made many tests) to find a colour map that works singificantly better than the original. This is also because, throughout the paper, we choose colourmaps that are as colour-blind friendly as possible. For instance, the "rainbow" colourmap would not possible to choose for this reason. However, we believe to have now found a better option using a log_norm and inversed version of the original colour map (matplotlib plasma). We have thus modified the figure accordingly.

-Reviewer 1 minor comment 25:

Line 656: "*Please can you briefly explain what this is: is it the fraction from a certain area of from supra versus subglacial?*"

Author reply: This is fraction of sink particle provenance from specific hydrological basins. To make this clearer: we added information to the sentence: "*For each sink polygon mapped (n = 49; Fig. 3a), we provide a high-resolution map of particle trajectories, along with an estimation of particle provenance fractions, i.e. the proportions of sink particles originating from specific hydrological basins (see section 2.4; Figure S1)*"

-Reviewer 1 minor comment 26:

Line 681: "*Personally I wouldn't present it as +/- like this, I'd give median and range separately. When I first read it, I thought it was the error and was surprised how high it was.*"

Author reply: We agree, and this echoes a comment from reviewer 2 also. Indeed a +/- more often refers to an error estimate whilst the goal of the IQR here is to quantify data dispersion and define the distribution. We have now changed all statistics reporting of this kind to : "with a cumulative glacial transport time of 6,361 yrs (IQR = 3,641 yrs)..." with the interquartile range in brackets after reporting the median number.

-Reviewer 1 minor comment 27:

Figure8: "Would be helpful to add a few key place names and basins to orientate the reader in these panels."

Author reply: We thank the reviewer for this comment. To adress this, we have now added a small inset to the figure allowing to see the location of the top panels and the Mount Saléve relative to the full alps (with the hillshade of the topography and country bordies + country codes). We prefer this option over adding more data on top of the maps in the original figure panels in order not to overlay the model and particle data : which we feel would overload the figure and would hide the more important information. With this inset we hope the goal of allowing the reader to better locate the region we focus on in this example has now been reached.

-Reviewer 1 minor comment 28:

Line 966: "*May be worth stating explicitly here that it can be used to target future work to narrow down uncertainties / verify flow paths at key sites. I think that's one of the really powerful things with this work - it tells us where we can get the most bang for buck for dating*"

Author reply: Many thanks for this great suggestion: we added a sentence: "*Our model may either slightly overestimate ice thickness over the Rhône and Solothurn glaciers during the LGM, or may be correct but sedimentological evidence for such momentary transfluence may be rare and not yet documented/dated. In either case, our high-resolution modelling helps target field sampling locations more precisely by producing particle trajectories that inform physically-plausible transfluence locations.*"

-Reviewer 1 minor comment 29:

Figure9: "*As for te figure above, I'd add some key place names / basins for context - I know you've probably spent a long time looking at the Alps, so know where everything is, but I'm less familiar!*"

Author reply: Thank you for the suggestion, following this comment we have now added a few reasonably well-known city names to the top panel of Figure 9, to help the viewer get a sence of the location. The trick is also to not overload the figure nor make any labels overlap with the Orange trajectories which are the most important data on this figure.

-Reviewer 1 minor comment 30:

Line 1043: "*This mini literature search is valuable in itself - do you have a table with the info summarised in supp info? If not, I would add.*"

Author reply: Many thanks for this comment. Indeed, we produced such a table: it is located in the supplementary materials under Table S1.

-Reviewer 1 minor comment 31:

Line 1072: "*the results of this analysis*"

Author reply: Change to the sentence was made accordingly.

-Reviewer 1 minor comment 32:

Figure 10: "*I like the idea of this figure but it's a bit hard to read. Cosnider making the yellow dots e.g. + but larger. The purple lines are very hard to see, so perhaps just a point to display them on a? I also find teh ice surface colours a bit hard to see. Maybe a hillshade or some contours to help it really show up?*"

Author reply: We thank the reviewer for this comment. We have now increased the size of the yellow dots (although there is a limit as its also important to visualize the precise location of the modelled transfluences with respect to the topography as this is a major result from our work) and also increased the size of the panel reducing white space to make the maps slightly bigger within the figure. We have also modified the colour of the location labels in Panel A for red with black outline (rather than pink) and white transparent background to increase visibility. After many tests (we honestly tried many different options), we however did not find a notably better combination of colours for the data shown on panel B. Displaying the modelled flowlines (most important for the transfluences) + the model output ice geommetry and surface elevation (enhanced by contours) + the hydrological basins outlines (important for their crossing with the flowlines: thus indicating the transfluences) + the underlying topography in places with a hillshade: is quite tricky altogether: especially when trying to make it colour-blind friendly. Please note that all figures are produced in very high resolution for the purpose of being zoomed-in on the digital paper version. Once zoomed-in we believe this figure becomes quite clear.

-Reviewer 1 minor comment 33:

Line 1182 *:* "*Personally, I think you're starting this section a bit negatively, given how much you have done. I'd suggest having a paragraph on the key take home points and things that can be done with the model - I think these appeared at the end of the intor, so I'd move them here and change the sub heading to e.g. Applications, limitations adn future work. Basically, make it really clear for someone reading this how they coudl use it and show off a bit!*"

Author reply: Thank you for the comment and nice suggestion. We agree, and we have now moved almost all of the content of the last introduction paragraph (the one which felt out of place) to the beginning of the Discussion: whose first section (4.1) title was now changed to "*Applications, limitations and future work*" , as suggested. This makes the discussion start on a much more positive note, with main take home messages and the added value of our work, followed by the paragraphs on limitations and future improvements suggestions, and then followed by the second discussion section (4.2) on wider implications. Its important to us to finish the discussion on the wider implications rather than on the limitations of the study, in order not to finish the reading on a negative note. We have now also removed this last paragraph from the introduction.

-Reviewer 1 minor comment 34:

Line 1193 *: "sediments"*

Author reply: change made accordingly.

-Reviewer 1 minor comment 35:

Line 1217 *: "This would be nice to add. Do we have empirical or process modelling data on how this occurs?"*

Author reply: Yes there are a few empirical field and laboratory studies on the subject. We have now added an extra sentence to mention some key example studies which may provide quantitative means of parametrizing this in a model, even though this remains quite challenging and dependent on many other processes: "*In future modelling work, more realistic provenance fractions may thus be obtained through parameterizations that reduce particle preservation as glacial transport time and distances increase. For instance, previous work attempting to empirically quantify, through either laboratory (e.g. Hooke and Iverson, 1995) or field (e.g. Hubbard et al., 1996) investigations, the deformation-induced comminution of subglacial sediments by analysing their facies and properties (e.g. clast shape and size, fractal dimension), could help implement such model parameterizations.*"

-Reviewer 1 minor comment 36:

Line 1236 *:* "I like the way you identity the limitations, but coudl you give an indication of how you might tackle them in the broadest sense and how challenging they are to either model and/or validate, E.g. it's very hard to get direct data on sediment evolution processes at the glacier bed, so it woudl be hard to validate if implimented."

Author reply: Thank you for this great comment. To address this, we have now added a few extra sentences to the discussion when mentioning possible future improvements to pursue, in order to provide thoughts about how they could be informed or how challenging they might be:

For instance here (line 1222):

"*In future work, modelling these complex mechanisms would require full coupling of both subglacial hydrology and sediment-transport modules to glacier-evolution models. Whilst such coupling has already been implemented in single-glacier modelling studies (e.g. Delaney et al., 2023), the added computational cost remains a challenge for large spatial and temporal (paleo) timescales, and the lack of observation data on subglacial and bed conditions leaves the numerous additional parameters of such schemes poorly constrained.*"

And here (line 1239):

"*In future modelling work, more realistic provenance fractions may thus be obtained through parameterizations that reduce particle preservation as glacial transport time and distances increase. For instance, previous work attempting to empirically quantify, through either laboratory (e.g. Hooke and Iverson, 1995) or field (e.g. Hubbard et al., 1996) investigations, the deformation-induced comminution of subglacial sediments by analysing their facies and properties (e.g. clast shape and size, fractal dimension), could help implement such model parameterizations.*"

And here (line 1255):

"*The accuracy of future coupled glacier-particle modelling may thus be increased by adding an erodibility index parameter controlling the seeding likelihood based on rock hardness, faulting, temperature-driven rock-permafrost conditions, and resistance to erosion, constrained by present-day geological observations and/or reconstructed past erosion rates (Gallach et al.,* *2021). A number of studies have already produced global (e.g. Moosdorf et al., 2018) or more regional Alps-specific (e.g. Kühni and Pfiffner, 2001) maps of erodibility indexes based on various geological attributes, which could thus be leveraged for improved model parameterization.*"

-Reviewer 1 minor comment 37:

Line 1267 *: "I guess it could also be used by people at specific sites of interest, where it's possible to generate such data."*

Author reply: We agree, and have now modified these sentences to accommodate this important additional point: "*An obvious future improvement would be to produce similar sink-to-source analyses for more specific sites yielding detailed glacial geomorphological mapping of ice-contact deposits, or for a more detailed Alps-wide map of individual glacio-terminal landforms that remain preserved to this day. However, the latter would require producing a digital (e.g. GIS database), open-access, Alps-wide map of preserved glacial geomorphology with geochronological constraints and a consistent naming convention (e.g. Glasser & Jansson, 2008; Clark et al., 2018). To our knowledge, such a valuable product is not yet available for the European Alps.*"

-Reviewer 1 minor comment 38:

Figure11 *: "I think you need to reconsider the colour scheme her e- I can only see blue!"*

Author reply: Please refer also to our reply to comment 24 as some of the reasoning overlaps: i.e. the nature of the particle density data is partly responsible for this. But the most important information rather than the density values are the shapes produced by the deposits: which ressemble glacio-terminal geomorphological features (e.g. terminal moraines): and we believe this figure already shows that nicely. However, to address this comment, we have now tested more combinations of colormaps and renderings. Displaying the topography + the model output data + the particle deposit data in spatial density scale + the ehlers LGM limit all in one map and in a a clear manner, whilst making sure the result is as colour-blind friendly as possible: is non-trivial. The best result we eventually managed to obtain was to go back to the original colour map but in log scale rather than linear.

-Reviewer 1 minor comment 39:

Line 1335 *: "Are there any specific implications for surge type glaciers? E.g. if we know where the desposits came from and how long they took, coudl we reconstruct surging? Probably a lot more complex in terms of the flow, but just wondering if there are potential applications there that coudl be noted?"*

Author reply: Thank you for raising this interesting point, indeed we also think it is likely that particle tracking of large particle numbers can also be valuable to study surging glaciers: if the glacier model used is capable of representing surging mechanics and surging events realistically. In that case the addition of particles would likely help better visualize and understand the complex internal ice motion dynamics associated with these events, and help tie those to preserved sedimentory deposits associated with surging events. We have now added a sentence in this paragraph to mention this example:

"*Lagrangian particle tracking coupled with glacier modelling essentially offers a mechanism to better visualize the time-transient 3D flow trajectories of simulated glacier motion (Figure S7). As a result, it can help to better understand contemporary and past internal glacier dynamics, including vertical ice motion, flow convergence and divergence, and the complex behaviours of merging glaciers. Provided that surge dynamics are realistically captured by the ice-flow model, particle tracking could also offer valuable insights into the transient flow complexity of surge-type glaciers and their associated sediment transport and deposition patterns*."

-Reviewer 1 minor comment 40:

Line 1340 : “*Please simplify teh language here.*”

Author reply: We have simplified this to : “Reconstructing the precise locations and lateral migrations of such suture zones in paleo glaciers, which reflect differences in driving stress and ice flux between two merging glaciers, can be crucial to explain:…”

-Reviewer 1 minor comment 41:

Line 1349 : “*Perhaps it comes in here, but worth saying the model can be used to target future dating work at key sites / areas of uncertainty, such as ice divides.*”

Author reply: We agree that this important point is worth stating again in this section. We’ve added a last sentence to the end of section 4.2.2 on this: “*Our Mont Salève case study (section 3.3.3) is a good example for which understanding the location and migration of the suture zone separating the Rhône and Arve glaciers, easily visible with particles on Figure 8 (panel a), is key in understanding the modelled provenance and transport pathways of specific ice-contact deposits in this region (e.g. the Mont Salève erratics). Moreover, such coupled glacier-particle modelling can help target most appropriate field sites for future dating and/or provenance analyses of ice-contact deposits.*”