# Authors' response on RC1

Julien Seguinot and Ian Delaney

Author comment on "Last-glacial-cycle glacier erosion potential in the Alps" by Julien Seguinot and Ian Delaney, Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2021-12-AC1, 2021

Dear Anonymous Referee #1,

Thank you very much for your positive comments and for your time spent reviewing our work. We try to address your comments one by one below, and highlight relevant changes made to the manuscript.

> *The study of Seguinot and Delaney presents a time-integrated model on the glacial erosion potential over the last 120 ka in the Alps. Authors tie the calculations on a previous study by Seguinot et 2018 who modeled the glacial extend over Alps' last glacial cycle by testing three different records on palaeo-temperature (GRIP, EPICA, and MD01-2444). Calculated basal velocities which base on the Parallel Ice Sheet Model PISM were used to test different glacial postulated erosional laws (Koppes et al., 2015; Herman et al., 2015, Humphrey and Raymond, 1994; Cook et al., 2020) focusing on the Rhine glacier area.*

> *The main achievement of the study is to combine a realistic, high-resolution model of glacial extension over a glacial cycle in a mountain range with assumptions on glacial erosion. Even though the utilized PISM code does not account for feedbacks of glacial erosion on bed topography, which makes it not directly comparable with common landscape codes on glacial erosion (e.g. Egholm et al. 2009; Sternai, et al., 2013), some relevant findings could be derived by this integrated high-resolution approach. This includes the observation of low erosion during glacier advance and maximum glacier extension, and the role of profile steeping during deglaciation and related increasing erosion rates.*

Thank you for this accurate summary of our paper.

## General comments

> *Authors decided to keep the paper short, referring most information on glacial model set up and resulting ice cover to the Seguinot et 2018 paper. This makes it no always very easy to read and needs checking in the original manuscript (for example, ice cover deviations model – field bases LGM extension).*

Indeed, it is our deliberate choice to avoid paraphrasing or duplicating content from the 2018 paper, where the preparation of the text and figures also involved a different author team. We believe this is justified given that both papers will be published open-access. Nonetheless, small additions were made. Please see our responses to your technical comments below.

> *The introduction gives a nice, relatively long (in relation to other chapters) overview on different aspects of glacial erosion and resulting features, and guides through problems to investigate them. Here, I don't see very clear how different aspects or parts in the introduction are specifically addressed in this study, i.e. which problems are exactly aimed to be solved of this large portfolio of mentioned gaps in the understanding of glacial processes. I think this could be better formulated and balanced.*

Our introduction is meant to revolve around two discussion points: the variable imprint of glaciers on mountain topography, and the link between climate and glacier erosion (somewhat addressed in the conclusions). This is followed by a short methodological bibliography of process-based and empirical glacier erosion laws, before we announce the scope of our work. A few key statements were added to try and better tie these different sections.

> *I think the study could also well contribute to the discussion on the elevation distribution of the cumulative glacial erosion over several cycles in the Alps (high elevations vs low elevation, e.g. Valla et al., 2011). A plot showing the integrated glacial erosion potential over (e.g. 100 m) elevation bins would easy to do and eventually an enlightening supplement summing up Fig. 5a.*

Thank you for the suggestion. Figure 5 was amended with the distribution of cumulative erosion potential over 100 m elevation bins. The resulting plot shows that most modelled erosion occurs below 2000 m, with the potential erosion volumes between 1000 and 2000 m elevation.

> *I would also recommend to make some regional statements on the distribution of the glacial erosion potential (Fig. 2). It is quite obvious that some tectonic massifs can readily be discriminated, e.g. the Tauern Window, Oetzal Crystallin complex, the Aare Massif, Mt. Rosa - Gran Paradiso and Pelvoux Massif. Is it the steepness of these low erodible crystallin massifs making the erosional potential appearing strikingly high? I think this should/could be discussed..*

Our calculations indeed produce locally high cumulative erosion potential in the aforementioned crystalline massifs. More accurate modelling of small-scale glaciers would be needed to provide an accurate answer to your question. Steep topography, though, is likely to be part of the explanation. A more substantial discussion of the high erosion potential values in these areas and the model limitations that hinder interpretation was added in the "age of the glacial landscape" subsection. This new passage reads as follow:

  "The validity of the model results at high elevation is discussable. Crystalline massifs such as the Ecrins, Gran Paradiso, Monte Rosa, Aare, Ötztal and Tauern Massifs locally exhibit a strikingly high erosion potential. However, the computation of glacier flow velocities on such steep surfaces is strongly limited by the model horizontal resolution of 1\,km, the shallow-ice glacier flow physics (Imhof et al., 2019), and PISM's current mass-conservation heuristics (Imhof, 2021). Besides, bergschrund (rimaye) processes likely to dominate interglacial cirque erosion at such altitudes (Sanders et al., 2012) are not captured by the velocity-based glacier erosion power-laws."

## Specific comments

> *Line 24 Maybe a bit odd to use 4 very old references from the Alps only (you hardly used more than 2 references throughout the MS and there are also high variety of glacial landforms in other mt ranges as you mentioned).*

We agree that the references are not directly relevant. The citation was reduced to the latest reference by Penck (1905) and moved within the sentence to clarify that it is specific to the Alps.

> *Line 33 I think that's not very easy to understand what landform you refer to? The "periglacial blockfields topped by glacial erratic boulders" (Wirsig et al., 2018)? Eventually be more precise on this would help readers.*

Agreed. "Characteristic landform preservation" was replaced with "preserved periglacial blockfields topped by erratic boulders".

> *Line 101 Could be misleading as (glacial and periglacial) cirque erosion processes are not really covered by any glacial erosion law discussed here (or any other I am aware of, Sanders et al., 2012).*

Thank you for pointing out this study. This particular sentenced was reworked to acknowledge not only the limiting resolution but also the lack of relevant erosion erosion processes. The reference was additionally incorporated in the relevant part of the discussion (see general comments above).

> *Line 116 ..while much OF the intra-montane..*

Thanks. Corrected.

> *Line 127 Higher precipitation increases ice flux and thus erosion, I guess? Would eventually helpful to mention (even though it might be referred in Seguinot et al., 2018).*

Indeed. The increase in ice discharge was made explicit.

> *Line 140 Can you be more precise what you mean by realistic? You mean because of the localized pattern? Maybe I am wrong but shouldn't the erosion potential at least at the lake Constance overdeepening (Fig. 7) not in the order of hundreds of meters (cf. Preusser et al., 2010) and the best fit rather (b) or (c) – at least from what I read from the transect (e-h)? Visually (a)-(d) seem not to correspond to (e)-(h) if (a)-(d) is also presented in meters (annotation at the bar is missing). For example, in (b) the maximum erosion potential is like >>1000 m (if in meters) while in corresponding (f) it seems clearly lower than 1000 m.*

This sentence was about the amplitude of the cumulative erosion potential, but we were probably a bit too fast deeming one erosion law "more realistic" than the others. We are not sure what the cumulative erosion potential of the last glacial cycle should be. Based on the estimates of total Pleistocene glacial relief from the suggested references, we now argue that no tested erosion law give results in the expectable range of last glacial cycle erosion.

  "With a total Pleistocene glacial relief on the order of a kilometre (Preusser et al., 2011; Valla et al., 2011), a cumulative glacial erosion for the last glacial cycle in the order of 10 to 100 m can be expected. However, none of the tested erosion power-laws fall within this range. Instead, the erosion law calibrated on tidewater glaciers (Koppes et al., 2015) yields cumulative erosion in the Rhine Valley in the orders of metres, while the three

erosion laws based on terrestrial glaciers (Humphrey and Raymond, 1994; Herman et al., 2015; Cook et al., 2020}, result in kilometre-scale integrated erosion potential. During the Last Glacial Maximum and much of the last glacial cycle, Alpine paleoglaciers were closer in size, slope (an important parameter as we argue in the next section), and climatic context to the present-day glaciers of Patagonia and the Antarctic Peninsula (Koppes et al., 2015) than to Franz-Joseph Glacier (Herman et al., 2015) and many of the glaciers included in the global compilation by Cook et al., (2020). This may help to explain why the reality appears to fall in-between the tested erosion laws."

Regarding Fig. 7, there is no mismatch between panels (a-d) and (e-h), but to improve readability we have reduced the number of colour levels on the maps, and changed the positions of ticks on the transects.

> *Furthermore, isn't the impression of the fit potentially very dependent on the initial model parametrization (Seguinot et al., 2018), i.e. the ice flux velocity? You should address these dependences!*

A paragraph was added under "choice of erosion law" to discuss the uncertainties on glacier sliding physics. Also including suggestions from reviewer #2, the new paragraph reads as follow:

  "The modelled pattern of erosion potential depends on PISM glacier physics and sliding model parameters. In particular, the pseudo-plastic sliding law exponent (q=0.25 in Seguinot et al., 2018) controls the sharpness of the transition between adherent and decoupled basal conditions. Recent ensemble validation of Antarctic Ice Sheet glacial-cycle simulations against geological and present-day observations (Albrecht et al., 2020a, b) support a higher value of q=0.75, and thus a sliding law closer to linear, which would perhaps result in a smoother distribution of sliding velocity and erosion potential. Lateral stress gradients missing from the shallow-shelf approximation stress balance could also contribute to moderate sliding velocity in narrow troughs (Herman et al., 2011; Egholm et al, 2012a, b; Pedersen et al., 2014)."

> *Line 163 Observing Alpine topography I find this result important, which can maybe also serve as explanation why e.g. (low erodible) areas away from the big troughs covered during glacial maxima only, do surprisingly often show no/very low degree in glacial modification (e.g. Ticino; Kelly et al., 2004).*

Thank you for pointing this out. The following sentence was added in this paragraph:

  "Nevertheless, it may explain why some areas covered during glacial maxima only, such as some valleys on the southern side of the Alps, appear to have experienced only little glacial modification of their topography."

> *Line 187 "time-transgressive radial pattern". I don't understand what you mean..*

This sentence was only meant to recall the aforementioned results. We rephrased to "the potential erosion patterns experience spatial shifts through the glacial cycle".

> *Line 195 Very much share this view!*

Good to know!

> *Line 197 Would recommend to be more precise. Guess you know that there are many, many cirques in the Alps as low as 1500 m (and even below) e.g. forming in areas outside the connected ice stream network in the SW and easternmost Alps. This can be revealed by a quick check at any higher resolution DEM or google earth.*

The statement was reworked and restricted to "the highest mountain cirques".

> *In the MS the word "yet" is very often used. Eventually consider reducing. The frequency is a bit irritating when reading.*

In several instances we replaced "yet" with "but" and "however".


## Figures

> *Fig. 2 Please indicate the outline of the connected ice stream network during the LGM (like in Fig. 4 of Seguinot et al., 2018). Especially in the eastern and SW Alps coverage largely deviates from what has been suggested from field data compilation (e.g. Ehlers and Gibbard, 2004). Even though outcomes might not be changing much, it might be helpful to know how much the %overlap is - erosional potential might change as fluvial topography turns into glacial one (e.g. Harbor, 1988) and this is probably not what you want to mix, I guess.*

The field-based LGM outline was added on Fig. 2. Computing a percent overlap is not straightforward. As for Fig. 4 in the 2018 paper, we use a manually modified version of the Ehlers et al. (2011) data. The original data presents numerous, expansive nunataks, many of which are found in accumulation area and thus directly incompatible with the mass-balance scheme used in the 2018 paper. However, the general eastward bias was discussed in two new sentences:

  "It should be noted, however, that all runs presented here show a systematic bias with excessive glacier cover in the Eastern Alps and a diminished glacier extent in the Western Alps (Fig. 2a; further discussed in Seguinot et al., 2018). Thus the modelled patterns of erosion potential certainly includes a similar bias."

> *Fig. 5 I have to confess Fig. 5a surprises me, there are really glaciers as low as 500 m.a.s.l (and even below) from 110 – 40 ka in the Seguinot et al., 2018 model?*

This is correct. It concerns only a small number of grid cells, primarily located on the southern slope of the Alps where topography drops abruptly from the highest peaks to deep valleys. This information was added to the plot by hatching the regions with fewer than a hundred ice-covered grid cells per elevation band. This highlights that low-elevation values are not always representative, as can also be confirmed in the new subplot showing the distribution of cumulative erosion potential over 100 m elevation bins. The distribution of glacier cover per elevation band over time (from which the hundred-cell contour was extracted) will be included in a new version of the companion dataset.


## References not in the manuscript:

In addition to the aforementioned changes, the Sternai et al. (2013) reference was added in the discussion of the vertical distribution of erosion with this new sentence:

    "Over longer timescales, though, the vertical distribution of erosion rates also depends on the erosional modification of topography (Sternai et al., 2013)."

Thank you again for taking the time to read our work and to give constructive feedback in these troubled times. We hope that you will find our answers satisfactory, apologize for the delay and will soon be submitting a revised and, we believe, improved manuscript

including the aforementioned suggested changes.