TC-2022-237
Brief Communication: Rapid ~335 10^6 m^3 bed erosion after detachment of the Sedongpu Glacier (Tibet)
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Revisions in response to referees

General response

We would like to thank the two referees for their thoughtful and constructive reviews that certainly helped to improve the paper. We implemented all recommended changes and in particular added information and discussion about the concentration of erosion in summer 2021 and about the general implications of the events with respect to landscape evolution.

Editor/referee comments are in *italic*, and our response in normal font.

An annotated version of our revised manuscript with track changes is attached.

Response to Referee #1, anonymous

General comments

The authors have analyzed the changes of the Sedongpu valley following the 2018 glacier detachment. Given its incredibly high mass movement activity, the Sedongpu catchment is currently of high interest to the scientific community. In that sense, any contribution is of interest and additional data is surely welcome. While I think that the submitted manuscript is interesting, I do question its brevity and the would therefore like to suggest a few amendments.

I have two suggestions to increase the value of the presented contribution:

The authors initially make the connection with long-term landscape evolution, but later provide only one sentence where this topic is picked up again (L100). I would encourage a more detailed discussion of the topic. I am no expert at the topic, but a brief literature search reveals that the observed erosion rates at Sedongpu are far beyond the norm. Of course, long-term erosion rates are unlikely to be a good indicator of short-term peaks, but a more detailed literature review can surely shed more light on this than what I have done here. For example:

Delaney et al. (2017) report an average of 5.4cm yr^{-1} over 28 years at Griesgletscher, Switzerland https://onlinelibrary.wiley.com/doi/10.1002/esp.4239

Hogan et al. (2020) report from values from Peterman Ice Stream that range from 0.5 mm yr^{-1} to 1.5 mm yr^{-1} during deglaciation cycles. https://tc.copernicus.org/articles/14/261/2020/tc-14-261-2020.pdf

Hinderer et al. (2013) up to 7000 t km^{-2} a^{-1} from glacierized basins in the European Alps (5 to 10 times larger than non-glacierized basins) https://www.sciencedirect.com/science/article/pii/S0012825213000032?via

%3Dihub

We modified text at several places and added a paragraph in the discussion section, see more details under major comment 2) of referee #2.

I very strongly encourage the authors to make their datasets open access to anyone. This would hugely increase the impact of this brief communication and surely provide the community with a really valuable dataset.

We will try our best without breaching the strict licensing conditions. We are definitely not allowed to make our DEMs open access, but could make dDEMs available for academic purpose. This is why we need to ask for requests.

Specific comments:

L48: How far to the confluence with the Brahmaputra?

Clarified that "Yarlung Tsangpo" is actually Tibetan for "Brahmaputra". Our study site is at the main branch of Brahmaputra even if Brahmaputra has a number of large other tributaries. See also response to ref#2 L37.

L40/41: the warmest months, the coldest moth

Done

L44: How much do you think the elevated bed contributed to the overall erosion volume? Can you quantify this?

See L52 comment below

L47: ran not run

Done

L52: This statement sounds a bit like the glacier slid off its sediment bed without any entrainment, which is likely not true. Can you quantify how much subglacial material was removed in the initial event (maybe using the ice thicknesses from Farinotti 2019 or Millan 2022?)

We added

“The theoretical ice thickness estimates for Sedongpu Glacier from Farinotti et al. (2019) agree on average well with the actual elevation loss 2015 – December 2018 due to the glacier detachment, suggesting that the $130 \cdot 10^6$ m^3 glacier detachment volume consisted to a large extent of (though likely sediment-rich) ice rather than basal sediments. This high ice content of the glacier detachment is confirmed by visual interpretation of the deposits (Kääb et al., 2021). The ice thickness estimates by Millan et al. (2022) are roughly double and more of the above estimates and measurements, likely because they are based on 2017–2018 glacier surface velocities, which were in the case of Sedongpu Glacier already elevated due to pre-detachment surge-like acceleration (Kääb et al., 2021).”

L66ff: Can you try to specify whether references to 2018 are before or after the detachment?

Good catch! Clarified.

L78: gradually, not gradual

Done

L81: worth mentioning

Done

Table 1: Can you additionally express the changes in erosion rates (e.g. m yr^{-1})? You say that the changes happened gradually, but it is hard to compare the different time periods because the time steps are very different.

Rough erosion rates included in the table.

Would you expect some seasonality based on the strongly varying precipitation amounts? Does the data show this? If not, why not?

One would expect that the erosion has some seasonal dependence with precipitation amounts, but the temporal sampling of our DEMs is too coarse for such conclusions. In fact, the most massive erosion in 2021 starts in June, during the rain season. As we explain below in response to referee #2, this erosion start is, however, not necessarily due to large precipitation amounts.

Response to Referee #2, Max Van Wyk de Vries

The authors have analysed a timeseries of digital elevation models to understand the post-detachment geomorphic change – specifically the formation of a deep canyon in the years following the rapid removal of Sedongpu glacier tongue. The paper is well written and the exceptional changes in this catchment will be of interest to the broader community. Some modifications to the paper in order to add a more in-depth exploration of some of the mechanisms driving the pulse of incision and the broader implications of these findings are needed. I believe that these changes can be made while remaining within the constraints of a 'Brief Communication'.

I have two major comments:

1) The reason for the extremely rapid erosion between May-Sep 2021 needs to be explored in more detail. As it stands the manuscript clearly addresses the reasons for the rapid post- glacial erosion, but does not explain why the rates of erosion were ~an order of magnitude higher during one specific period, particularly a period not immediately following the detachment. This seems like one of the most important findings and one which may have wider implications for our understanding of these extreme erosive events. Why did the deposit experience a sudden change ~3 years post-detachment? The limited discussion about precipitation anomalies and other potential drivers needs to be expanded and moved to the methods/results instead of the discussion.

We added new information to the results section and additional discussion:

"Between Dec 2018 (i.e. shortly after glacier detachment) and Apr 2021 the erosion was mainly concentrated along the drainage stream that developed through the detachment area and corresponding avalanche path towards Yarlung Tsamgpo (Fig. 2b). Suddenly in early June 2021, major erosion activity started at the point where the drainage stream left the former glacier bed (star in Fig. 1b and c, Fig. 2b). From this point in time and space, massive but gradual up-valley retrogressive erosion formed the main canyon until end of Aug 2021. Assuming gradual constant erosion activity over June–August 2021 gives an extreme sediment flux of 3 10^6 m^3 every day over 3 months."

And

"The main erosion activity seems however rather to have been an autonomous, and perhaps self-enhancing, retrogressive destabilisation that, once triggered, formed the erosion canyon independent of precipitation amounts. This theory implies easily erodible, unconsolidated sediments, perhaps well water-saturated. The fact that the massive erosion activity in 2021 started exactly at the intersection of the former glacier boundary and the drainage stream suggests that the former glacier bed was much more easily eroded than the surrounding moraines. Once a comparably stable potential protective surface layer on the former bed was incised through stream erosion, the underlying weak sediments

could be mobilized. Alternatively, or additionally, enhanced stream erosion could have increased the terrain slope, or even undercut, at the location of the erosion initiation. Such processes would not necessarily require any particularly high precipitation amounts and only be dependent on the time needed for the stream erosion to reach a (local) destabilisation threshold related to slope or spatial variation of sediment properties. Precipitation data at the Nyingchi station, ERA5 reanalysis data, and GPM IMERG satellite-derived precipitation data all suggest very little precipitation during the first half of August 2021. Still, Sentinel-1 radar data suggest continued massive erosion during that period. High precipitation amounts could have particularly saturated the sediments to make them prone to destabilisation, or could have contributed to accelerated stream incision or critical increase in local terrain gradients, though."

We further add now a Supplement to the paper containing precipitation data and the animation of repeat Sentinel-1 data, illustrating the gradual erosion during summer 2021.

2) The balance between results and discussions in this paper is heavily weighted towards results (L35-93). Even the discussions (L94-134) dedicate quite a lot of space to evaluating the specific findings of this study with a fairly limited consideration of the larger scale implications. There is a rich literature considering topics such as the evolution of post-glacial landscapes, the magnitude-frequency distribution of sediment transport events, the relative erosion rates of glacial and fluvial landscapes, and volumes of sediment removed from the Himalaya on different timescales. I would not expect the paper to discuss all possible implications in detail, but the impact of this paper will be substantially reduced if the (very important) findings are not more effectively placed within the context of the broader literature.

We modified the text at several places and added a paragraph in the discussion section:

"The wider implications of the massive 2018–2022 erosion from the Sedonpgu basin for mountain landscape development and sediment fluxes depend on the spatial and temporal reference scales considered, including the significance of the event in the magnitude-frequency distribution of mountain sediment transport. Even compared to rates of pro- and post-glacial erosion that have so far been termed "ultra-rapid" (Meigs et al., 2006) the rates found in the Sedongpu valley since 2018 are exceptional. Compared to other glacier forefields which typically show post-glacial erosion rates in the order of cm a^{-1} (e.g., Delaney et al., 2018), the erosion volume at the former Sedongpu Glacier since 2018 is equivalent to several millennia of such average erosion rates. For entire mountain ranges hosting glaciers typical denudation rates are in the order of mm a^{-1} (e.g., Gabet et al., 2008; Hinderer et al., 2013; Thiede and Ehlers, 2013). Distributing the 2018–2022 Sedongpu erosion volume to the entire area of the Brahmaputra catchment upstream of the location where the river leaves the Himalayan arch (Pasighat) gives 1–2 mm (depending on whether the rock avalanches are included or not), i.e. the recent Sedongpu erosion volume is by order of magnitude equivalent to the annual denudation rate of a ~250,000 km^2 catchment. This implies that one or a few such events, triggered by glacier disappearance, can significantly vary the erosion rates of even one of the largest mountain river catchments on Earth."

Minor comments line by line:

L6 "130 10^6" – is there an uncertainty associated with this that can be quoted? There are a number of places throughout that volumes are given without uncertainties (e.g. L95, 96, etc), ideally these would all include an uncertainty from the discussed methods in L 60-65.

Added uncertainties at a number of places. In addition we managed now to process the 2022 DEM at the same accuracy as the other DEMs. The respective explanation for the 2022 DEM was removed.

L7 remove 'drastic'

Done

L10 Here, as a first-time reader, I am expecting to get some information about why there was extremely rapid erosion in 2021 specifically. I am left with a few questions in mind otherwise. The sentence "The mass was transported […]" on the other hand doesn't add very much.

We modified the abstract and added that the summer 2021 erosion peak was through temporally concentrated but still gradual retrogressive erosion into the former glacier bed, or a series of "smaller" events. (More details above and under L75-79 comment).

L12 Ending the abstract with a hint about the broader implications of the work would be useful.

Done

L14-34 This introduction is very well written. Concise, yet sets the scene well.

Thanks

L25 I am not entirely convinced that a detachment can be considered a direct analogy of longer-timescale glacial retreat and landscape exposure as presented here. The rate of change matters – this detachment led to the instantaneous exposure of a very large area of unconsolidated sediment, which may have been more likely to partially stabilize if exposed gradually (e.g., through vegetation growth or other processes). A slight change in wording to get this across would be useful. You do discuss this later on L120 onwards.

We term the analogy now "indication of the maximum erosion potential that might else be mobilized over longer time scales of gradual glacier retreat".

L36-45 I am not sure this fits within the subheading '2018 glacier detachment' but is instead more general background information. Move to the intro or its own subheading?

Agreed. We put this information in a new section "Study site".

L37 Is the Yarlung Tsangpo a 'tributary' to the Brahmaputra, or another name for the main branch of the same river?

To our best knowledge there are different perceptions around. We use now the one used by among others the Encyclopedia Britannica, i.e. Yarlung Tsangpo (Tibetan name) for the upper (=Tibetan) reaches of Brahmaputra.

L44 Reference for 'so called elevated bed'

Added a reference

L52 "leaving the bed of the Sedongpu glacier uncovered by ice" is confusing. If I understand correctly then the ice was gone, so the area is no longer the 'bed of the glacier'! Perhaps an alternate phrasing would be better, such as 'leaving the sediment previously beneath the Sedongpu glacier entirely exposed' or similar.

Changed

L56-64 Again, this first paragraph is not a great fit for the heading. This appears to be 'methods', not sure if it is best in its own heading or with the current heading modified to better represent it?

We put this information in a new section "Data and Methods".

L75-79 Here is where details are seriously lacking about the extremely rapid erosion in summer 2021. The only real information about it here is "the massive erosion happened gradual, or at least in a series of smaller events". Please expand and discuss the potential drivers of this here (meteorological data or other) and the mechanisms by which the mass may have been removed (I am guessing some form of landslide/debris flow to evacuate that quantity of material in such a short time).

See response to above major comment. We added according explanation to the text.

L81-85 Can you explain briefly why you consider this noteworthy? This is not immediately clear. Do you think that these subsequent avalanches played a role in destabilizing the sediment pile?

Modified to read "These rock-ice avalanches are worth mentioning as their deposits will have contributed to the ice and sediment properties in the valley, and could have also directly affected the ice and sediment stability there, for instance the Sedongpu Glacier detachment."

L87-88 Is this necessarily remarkable for a river of this scale? Also is there definitely no volume gain at all? It looks like a delta was constructed from the optical imagery in Fig 1.

We removed "remarkably", but still think this is important information that we would like to keep. Between some individual DEMs there are of course significant elevation changes in the river bed but they seem to be removed in sum within quite short time periods (few years maximum). The new delta volume is largely balanced by strong river erosion along the Yarlung Tsangpo just below the delta (likely due to changed river course) rendering the overall mass balance over and around the delta area quite small compared to the massive imported volumes.

L90-92 I can understand that an investigation of the routing of this sediment pulse be relegated to a 'further study', but this study will be easier to conduct if more baseline discussion about the sediment pulse is in this paper.

Done. See response to above major comment.

L95-96 Can you add the uncertainty to these numbers? Also, what is the distinction between 'rock' and 'sediment' – surely sediment is just a form of rock. Do you mean to distinguish between bedrock and sediment?

Done

L98-99 'several tens to hundreds', 'few weeks to months', 'up to several metres' – this sentence has a lot of vague terms. Can you just replace with the actual exact numbers which you have in the results above? They will be more informative.

Done

L102-103 People have mixed views about rhetorical questions, I am OK with them in general. However, I am not sure you really respond to this in any detail in the rest of the paragraph. Perhaps remove it, or keep it in an expanded discussions section about the broader implications (that is needed in any case).

Sentence modified and discussion added in response to above major comment.

L103-104 "The subglacial material from below this glacier seems especially easy eroded." As far as I can tell you haven't really presented the data to support this. We know that is was eroded, but if the erosion was driven by an extreme rainstorm or similar then it may not necessarily be particularly easily erodible?

We modified the sentence to list soft sediments as one possible cause of the rapid erosion. We also added discussion about the temporal concentration and cause of the erosion in response to above major comment. This discussion points also to soft (or else highly erodible) sediments.

L106-110 This exploration of possible causes is too brief. It might be useful to have a plot subpanel showing the precipitation data, and possibly exploring reanalysis (MSWEP/ERA5-land/CHIRPS) or satellite-derived (GPM IMERG) precipitation over the area of interest would be useful. These have low spatial resolution (0.05-0.1 degree) and have errors in areas like this, but may be useful for revealing relative patterns.

We add now a Supplement to the paper, containing meteorological data (ERA5 and station data).

L117 "Such elevated glacier beds are widespread in most glacierized mountains on Earth" should have a reference.

We added a reference to elevated sediment beds in the site description. We modified the sentence to refer to sedimentary beds in general, using Zemp et al 2005 as reference.

L126 remove 'impressively'

Done

L126-132 There are hints of discussion of the results in a broader context, but the broader literature is mostly absent. Please add in some external context to better highlight why these results are particularly relevant.

See response to major comment 2)

Data availability – It is a shame that the data cannot be shared more easily, but I understand that this is a limitation of these commercial datasets.

We will try our best without breaching the strict licensing conditions. We are definitely not allowed to make our DEMs open access, but could make dDEMs available for academic purpose. This is why we need to ask for requests.

Fig 1 and 2 – the meanings of the black and white dashed lines on the maps are not easy to find. Could you add some info about these to the caption? Also, the white boxed in Fig 1 are not easy to see, perhaps another colour would contrast better with the ice?

Modified in particular Fig 1 and added explanations in the figure.

Fig 2 – I am not sure how this may best be integrated into the current figure, but the erosion would be more intuitive and easier to compare as a rate (m/yr of erosion for example) than simply an elevation loss. Could this be overlaid onto the existing color legend?

We are unsure if showing erosion rates (instead of absolute changes or in addition) works well. We admit we haven't found a completely satisfying solution. The problem is that the rates are randomly dependent on the times of DEMs. For instance for the 2021 erosions, should we use the DEM dates as reference time or the shorter time period where the erosion actually happened? We believe showing the measured elevation changes is the most direct and re-usable result, free of hypotheses about the rate reference time. We added erosion rates now in Table 1, believing that the table offers more flexibility to express these erosion rates than the figure. We referred now in the figure caption to the table.