https://doi.org/10.5194/tc-2022-237
Preprint. Discussion started: 13 December 2022

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Brief Communication: Rapid ~335 10^6 m^3 bed erosion after detachment of the Sedongpu Glacier (Tibet)

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Abstract. Following the 130 10^6 m^3 detachment of the Sedongpu Glacier (south-eastern Tibet) in 2018, the Sedongpu valley underwent drastic and rapid large-volume landscape changes. Between 2018 and 2022, and in particular during summer 2021, an enormous volume of in total ~335±5 10^6 m^3 was eroded from the former glacier bed, forming a new canyon of up to 300 m depth, 1 km width and almost 4 km length. The mass was transported into the Yarlung Tsangpo (Brahmaputra) River and further. Several rock-ice avalanches of in total ~150±5 10^6 m^3 added to the total rock, sediment and ice volume of over 0.6 km^3 that were exported from the basin since around 2017.

1 Introduction

Current retreat of mountain glaciers uncovers large areas of unconsolidated sediments that were previously held under ice and thus protected against most direct impacts by weather and climate. After glacier disappearance these areas are subject to erosion processes at different time scales, from slow century-long background denudation to rapid mass loss by sediment-rich flows such as debris flows (Ballantyne, 2002; Carrivick and Heckmann, 2017; Williams and Koppes, 2019). Recent retreat of mountain glaciers is likely contributing to increased debris-flow activity and thus climate-change driven increase in mountain hazards (Zimmermann and Haeberli, 1992; Ballantyne, 2002; Hock et al., 2019). Glaciers retreat comparably slow, over many years to decades, so that the full potential erosion volume of formerly subglacial soft-beds is difficult to estimate from the usual successive bed erosion that follows gradual glacier retreat. The reconstruction of original subglacial sediment volumes or eroded volumes, respectively, is difficult at the locations of former valley glaciers, unless significant parts of the glacier bed are still preserved.

Rare but massive glacier detachments offer a unique natural experiment to investigate what happens to a glacier bed once the glacier above it is rapidly removed, mimicking a time machine of what might happen else over longer time scales of gradual glacier retreat. During such large-volume detachments entire low-angle valley glaciers are removed within minutes (Kääb et al., 2018; Jacquemart et al., 2020; Kääb et al., 2021), leaving their beds suddenly exposed to weather and climate impacts. Low-angle glacier detachments seem to be associated with particularly soft, and thus easily erodible basal sediments (Gilbert et al., 2018; Kääb et al., 2021). A very recent and at the same time one of the largest glacier detachments known to date is

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the 2018 Sedongpu, Tibet, event. In this study, we investigate the development of the glacier bed after glacier removal in order to draw conclusions about bed stability and erosion potential, the landscape evolution in response to glacier loss, and the associated hazard potential. We summarize key site information and the 2018 glacier detachment, quantify the glacier-bed volume changes until today (2022) and other landscape changes in the basin, and discuss and conclude about our findings.

2 The 2018 glacier detachment

The Sedongpu glacier was situated in south-eastern Tibet (29.80° N, 94.92° E), at an elevation of about 3700 m asl., just 4 km north of the Yarlung Tsangpo River, a major tributary to the Brahmaputra, which the Sedongpu valley joins at an elevation of around 2700 m asl. Highest point of the Sedongpu catchment is the Gyala Peri peak (7294 m asl.; Fig. 1). The study site, in particular the western flank of Gyala Peri represents extreme topography in terms of relief and overall slope angles. At the Nyingchi meteorological station (c. 3000 m.asl., c. 50 km west of Sedongpu), warmest months are July and August (mean daily maximum around 20 °C, mean daily minimum 13 °C), and coldest month is January (mean daily maximum 4 °C, mean daily minimum –8 °C). Highest mean monthly precipitations at Nyingchi are around 115 mm/month in July and August, and lowest in November and December with around 10 mm. Sedongpu glacier rested on a so-called elevated bed and the glacier surface had a c. 30-50 m higher elevation than the closest valley floor surrounding it. The study wider region shows the strongest glacier volume losses currently found in High-Mountain Asia (Hugonnet et al., 2021).

In addition to a number of smaller mass flows from the catchment until 2017, two 17 and $33 \cdot 10^6$ m^3, respectively, rock-ice avalanches from the Gyala Peri west flank run over the Sedongpu glacier late in October 2017 (Kääb et al., 2021; Li et al., 2022). Following the 2017 rock-ice avalanche(s), the main Sedongpu Glacier underwent drastic changes. Ponds developed on its surface and along the margins, surface velocities increased from a background velocity of ~0.3 m day^{-1} in 2017 to 25 m day^{-1} in mid-October 2018 (Kääb et al., 2021; Zhang et al., 2022) and the glacier surface showed increased crevassing. In two parts, on 16 Oct 2018 and 29 Oct 2018, the entire glacier tongue of in total $130 \cdot 10^6$ m^3 detached, and additional ~44 10^6 m^3 from surrounding moraines, leaving the bed of Sedongpu Glacier uncovered by ice. The mass temporary dammed up the Yarlung Tsangpo River, (Liu et al., 2019; Tong et al., 2019; Wang et al., 2020; Kääb et al., 2021; An et al., 2022; Zhang et al., 2022).

3 Rapid and massive bed erosion

Here, we mainly generate and investigate optical stereo data acquired by the Pleiades and Spot 6/7 satellites. We use the MicMac software (Rupnik et al., 2016; MicMac, 2022) to produce DEMs and orthoimages of 13 Nov 2015 (Spot 6 tri-stereo; before detachment), 30 Dec 2018 (Pleiades tri-stereo; two months after detachment), 12 Jan 2020 (Spot 7 stereo), 30 April 2021 (Pleiades tristereo), 19 Sep 2021 (Pleiades stereo), and 4 Nov 2022 (Spot 6 tristereo). All DEMs are generated and co-

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registered using standard procedures. Elevation and volume changes between our repeat DEMs can be estimated in different DEM combinations that should then sum up to the same amount. From the associated triangulation (or loop) errors we obtain an average uncertainty for our volume estimates of around ±1 10^6 m^3. From stable ground areas we estimate a standard deviation of elevations of ±4 m (for the 2022 DEM ±15 m, see Fig. 2 caption) and a standard error of mean elevation changes over the glacier and rock avalanche sites of around ±1 m, translating to an uncertainty of around ±5 10^6 m^3 for the volume change estimates. We choose the latter conservative estimate as our volume change uncertainty.

The most prominent elevation change over 2015–2018 is the glacier detachment from 2018 (Fig. 2, Tab. 1) (Kääb et al., 2021). Maximum detachment depths over the glacier area were c. 200 m. The total elevation changes 2018-2022 show a massive erosion pattern over much of the former glacier bed and its surrounding, amounting to about 335±5 10^6 m^3 , 2.5 times the detached glacier volume, and with maximum erosion depths of 360 m and an average of 135 m over an area of 2.5 km^2 (Fig. 2, Tab. 1). Between 2018 and 2020, erosion depths of up to 30–50 m can be found at limited areas along the deepest part of glacier detachment area. The elevation changes January 2020 to April 2021 display a similar pattern. The April – September 2021 elevation changes contribute the by far largest part of the 2018–2022 erosion of the glacier bed; 279±5 10^6 m^3 with a maximum depth of around 310 m. During September 2021 and November 2022 another around 32 10^6 m^3 were eroded from the area of the newly formed canyon.

To better understand the massive erosion amounts detected between the 30 April and 19 September 2021 DEMs, we investigated optical and radar satellite data during this time period. Due to almost permanent cloud cover during this season over the study site only very few useful optical data (Planet, Sentinel-2, Landsat) are available, and the most dense information stems thus from Sentinel-1 radar data. Combined, these data show that the massive erosion happened gradual, or at least in a series of smaller events, mainly during June–August and into early September 2021.

4 Rock-ice avalanches and river erosion

During 2018–2022 two other prominent landscape changes in the catchment are worth to be mentioned. Further rock-ice volumes of in total 100±5 10^6 m^3 were lost in the western flank of Gyala Peri, from the same area as the 50 10^6 m^3 rock-ice avalanche(s) of 2017, mentioned in Section 2. Of these roughly 100 10^6 m^3, 50 10^6 m^3 failed over Jan 2020–Apr 2021 (mostly on 22 March 2021; Zhao et al. (2022)) and another 50 10^6 m^3 during Apr 2021 – Nov 2022, all from the same area in the mountain flank (Fig. 1). Second, our DEMs include also a reach of around 6 km downstream of the location where the Sedongpu valley joins the Yarlung Tsangpo River. The fan of the Sedongpu valley shows a sequence of elevation gains and losses in response to the rock-ice mass flows from the Sedongpu valley, but remarkably, there is no significant overall volume gain in the fan area and the ~6-km reach (Fig. 2). This suggests that the river was able to transport further most of the massive amount of sediments that were deposited in particular during the 2018 glacier detachment and the June–September 2021 erosion peak. It should be interesting to investigate in a further study, whether and where signs of

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deposition of such large volume can be observed along the Yarlung Tsangpo and Brahmaputra River (Zhao et al. (2022) mention increased river turbidity 200 km downstream after the March 2021 rock-ice avalanche).

5 Discussion and conclusions

In sum, since 2017 and until November 2022 around 659 10^6 m^3 rock, sediment and ice debris have been exported from the Sedongpu catchment, most of it rock and sediments, and 335 10^6 m^3 of it eroded alone from the bed of the former Sedongpu Glacier and its immediate surrounding. In the optical satellite images we find no indication of substantial amounts of massive ice in the latter volume (An et al., 2022). This extreme erosion amount corresponds to erosion rates of several tens to hundreds of metres within a few weeks to months for the erosion area itself, or up to several metres if calculated as a mean for the entire basin area (total ca. 65 km^2, c. 50 km^2 of it draining towards the Sedongpu Glacier). Such "ultra-rapid" rates of paraglacial landscape response (Meigs et al., 2006) are to our best knowledge among the highest currently found on Earth.

To what extent can general conclusions be drawn from the extreme erosion volumes and rates that originate from the recently and rapidly uncovered bed of Sedongpu Glacier? The subglacial material from below this glacier seems especially easy eroded. This is in line with the assumption that large-volume detachments of low-angle valley glaciers seem to be associated with particularly soft glacier beds (Gilbert et al., 2018; Kääb et al., 2018; Kääb et al., 2021; Leinss et al., 2021). Precipitation data from the Sedonpgu catchment are not available to us and could in such extreme topography substantially differ from the measurements at Nyingchi, 50 km to the west. At Nyingchi, during June–mid September 2021, 28 days with precipitation amounts > 10 mm are recorded, six of which with 40–70 mm. These total and daily amounts seem to be substantially higher compared to the same time period in other years. The massive 2021 erosion could thus have well been triggered by exceptionally high precipitation amounts and rates.

We have not systematically examined the erosion volumes after the other glacier detachments listed in Kääb et al. (2021). From visual interpretations of satellite imagery, though, we do not find equally extreme erosion in these other cases as found for Sedongpu, but note that some of the detachments are indeed associated with substantial post-detachment erosion activity (e.g., Flat Creek (Jacquemart et al., 2022), Amney Machen, Rasht valley/Petra Pervogo range). Another special circumstance involved in the extreme erosion in the Sedongpu valley, in addition to the potentially especially soft sediments, could be the elevated glacier bed where particularly large amounts of sediments were stored underneath the glacier, thus available to erosion. Such elevated glacier beds are widespread in most glacierized mountains on Earth. Even if not fully understood, they are a sign of an imbalance in sediment flux where the production exceeds the export capacity from a glacier catchment (Zemp et al., 2005) – not surprising for the comparably small Sedongpu catchment (total ca. 65 km^2, ca. 50 km^2 draining towards the glacier) that includes an enormous rock wall with substantial rock avalanche activity. Another open question is whether the erosion volumes at Sedongpu after rapid removal of the glacier are higher than they would be after gradual glacier retreat over decades and centuries. Some self-stabilizing effect could come into play over longer time intervals that

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does not act during rapid erosions, or vice-versa a self-enhancing process could act under such rapid erosions. At least over decadal to centennial time-scales, the recent events at Sedongpu Glacier seem to represent a rapid and irreversible process of landscape transformation from a sediment-filled glacier valley to a glacier-free one with a deeply incised canyon.

The events at Sedongpu impressively confirm that glaciers are able to protect their soft beds against massive erosion. Once uncovered, the erosion potential of soft glacier beds is here demonstrated to be possibly enormous for some glaciers in terms of volumes and rates. Such erosion could be particularly extreme under the existence of fine-grained subglacial sediments, and – possibly combined – for elevated glacier beds where especially large amounts of subglacial sediments are stored. The 2018–2022 landscape development at Sedongpu represents an extreme example of rapid paraglacial slope response, a process that is indeed expected to be potentially particularly strong close to the time of glacier loss (Knight and Harrison, 2014). The changes at Sedongpu highlight an extreme glacier erosion potential and hazards related to it from debris flows and impacts on rivers. Such consequences of climate change in glacierized mountains have so far not been considered at this magnitude.

Code availability

The DEMs were generated using the open-source software MicMac (MicMac, 2022).

Data availability

Sentinel-1 and Sentinel-2 data are freely available from the ESA/EC Copernicus Sentinels Scientific Data Hub at https://scihub.copernicus.eu (Copernicus, 2020). Planet data (Dove and RapidEye) are not openly available as Planet is a commercial company. However, scientific access schemes to these data exist (https://www.planet.com/markets/education-and-research/). The original Pléiades and Spot stereo images are commercial (Airbus) and under academic license not transferable to other users. The derived DEMs can be made available on request for Academic use as defined under the Airbus license.

Author contribution

A.K. developed the study concept, wrote the text, did most analyses and prepared the figures. L.G. prepared the DEMs, and commented to and edited the text.

Competing interests

All authors declare that they have no competing interests.

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Acknowledgements

This study was conducted under ESA Glaciers_CCI and EarthExplorer 10 Harmony projects, and the University of Oslo "EarthFlows" research initiative.

Financial support

This work was funded by the ESA project Glaciers_CCI (4000127593/19/I-NS), and the ESA EarthExplorer10 Mission Advisory Group (4000127656/19/NL/FF/gp).

Table 1: Volume changes in the Sedongpu (Tibet) catchment over 2015–2022 as a consequence of glacier detachment, glacier bed erosion and rock-ice avalanches.

DEM data	Volume change glacier location (10^6 m^3, M m^3, ± 5)	Maximum elevation change (m)	Comment	Volume change rock-avalanche site (10^6 m^3, M m^3, ± 5)
13 Nov 2015				
	-174	-200	Oct 2018 glacier detachment, c. 130 10^6 m^3 from glacier, rest surrounding moraine	-50
30 Dec 2018				
	-12	-50		-1
12 Jan 2020				
	-12	-70	Contribution of rock-ice avalanche to changes at glacier location unclear	-50
30 Apr 2021				
	-279	-310	Erosion mostly in June–August 2021	-10
19 Sep 2021				
	-32	-120	Contribution of rock-ice avalanche to changes at glacier location unclear	-40
4 Nov 2022				
12/2018-11/2022	-335	-360	Maximum depths not at same location	-101
11/2015-11/2022	-508	-360		-151

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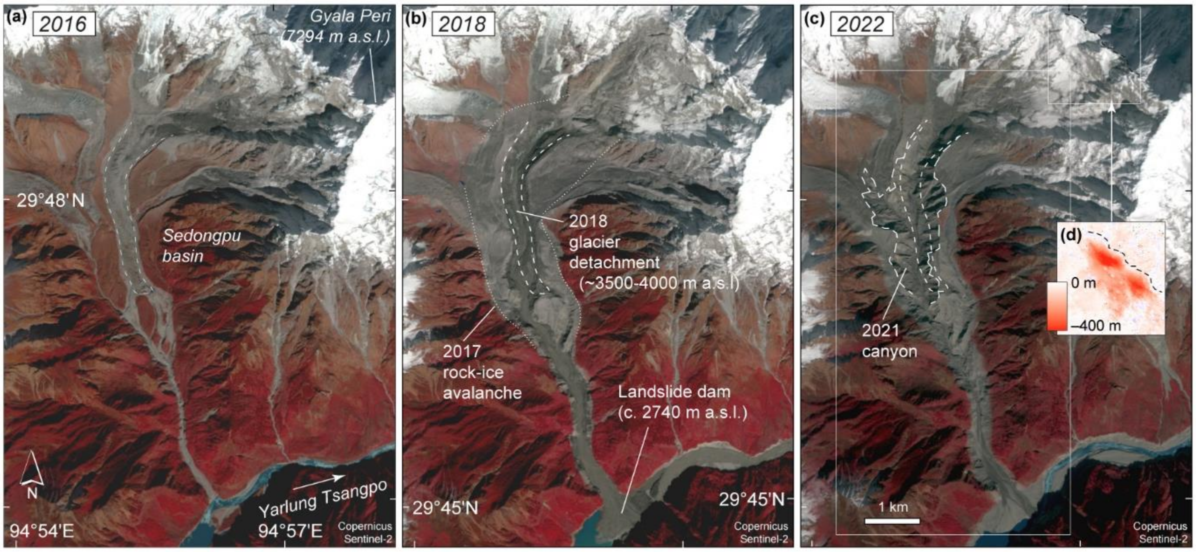

Figure 1: Sedongpu basin on (a) 20 Nov 2016, (b) 31 Oct 2018, and (c) 19 Nov 2022 (credit: Copernicus Sentinel data). In 2017 a large rock-ice avalanche passed over the Sedongpu Glacier and in 2018, just before image (b) was taken, the glacier detached completely. Since then, a large ~335 10^6 m^3 canyon eroded at the location of the former glacier bed with by far highest erosion rates during summer 2021. (d) Elevation changes 2015–2022 near the north crest of Gyala Peri showing the cumulative volume loss from three major ~50 10^6 m^3 rock-ice avalanches. The small white rectangle indicates the position of the elevation change inset (d). The large white rectangle indicates the location of Fig. 2.

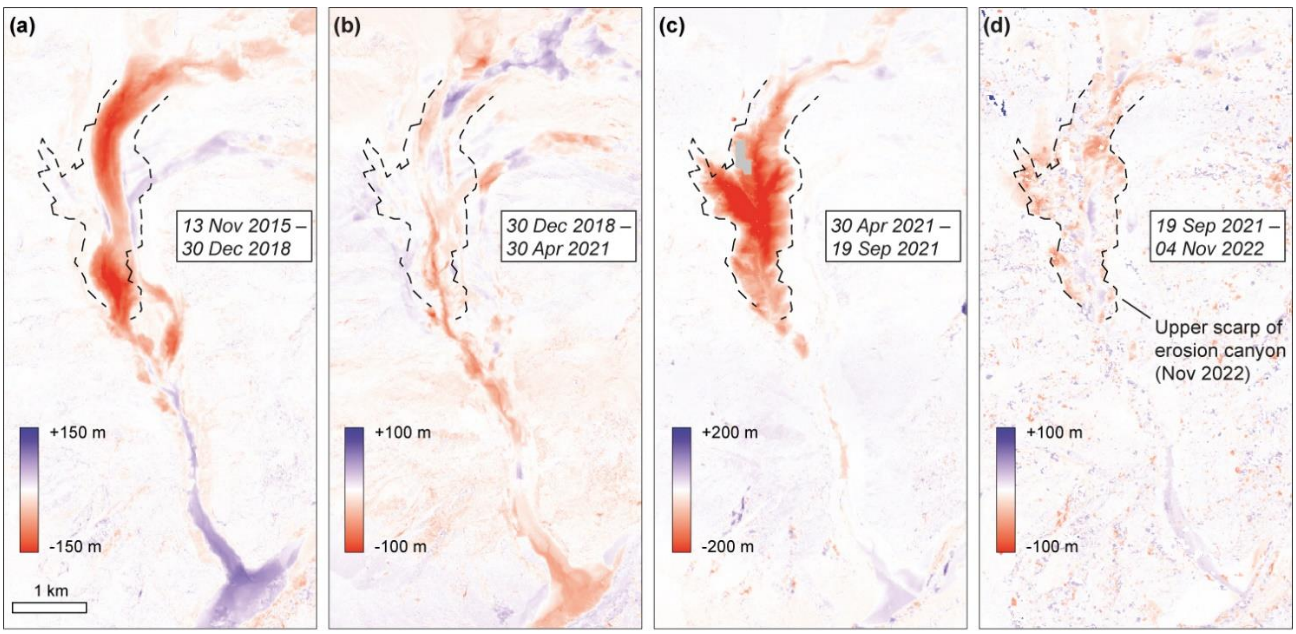

Figure 2: Elevation changes over four periods (a)-(d) as derived from DEMs from optical satellite stereo data (Pleiades and Spot 6/7, stereo and tri-stereo). Note, the value ranges of the elevation change legends vary between panels, depending on the magnitude of observed changes. The 2021–2022 DEM differences are more noisy than the others because the 2022 DEM was derived from Spot 6 data (lower resolution than Pleiades) with particularly small base-to-height ratios, in addition containing some fresh snow in higher terrain.

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