# Glacier detachments and rock-ice avalanches in the Petra Pervogo range, Tajikistan (1973–2019)

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Abstract. Glacier detachments are a rare, but hazardous, phenomenon of glacier instability, whereof only a handful have been documented to date. Common to all known cases are the large detached volumes of is that many million cubic meters of ice and long runout distances. detached from the bed of relatively low-angle valley glaciers and turned into long-runout mass flows. Recently, two detachments of smaller size such detachments were observed in the Petra Pervogo range , north west of the

- 5 Pamir mountains, in Tajikistan. Using a variety of satellite images, we imagery, including Landsat 1–8, Sentinel-2, ASTER, Tandem-X, Worldview, and Keyhole, we characterized these events and identified in total 9 detachmentsand several iceand rock avalancheswhich occurred 17 mass flows involving glacier ice (detachments, ice, and rock-ice avalanches) that clustered in four different catchments between 1973 and 2019. The avalanche run out distances vary between runout distances range from 2 and to 19 kmand detached volumes range between 2 and, and the largest detached glacier volume was 8.8 × 10<sup>6</sup> m<sup>3</sup>.
- 10 Seven out of nine detachmentsGlacier surging seem to be frequent in the Petra Pervogo range. 11 out of 13 detachments, ice or rock-ice avalanches occurred between July and September in years with temperature above the mean annual air temperatures above the trend of the past 46-yearstrend. No active glacier surge was observed immediately before detachment, but elevation model (DEM) differences indicate a surge-like behavior about 10 years before the two largest detachments. Instead, one glacier retreated before detachment while the other remained stagnant before increased sliding pronounced the impending detachment.
- 15 To put results into a regional context, we analyzed DEM differences over the entire Pamir range and found. The relatively large number of locally clustered events indicates that the Petra Pervogo range has particularly favourable conditions for glacier instabilities. The images and geology of the region suggest that easily erodible lithologies are widespread. These soft lithologies may be one reason for the high density of surging glaciers that we detected in the wider Pamir region (237 surging glaciers, predominantly in the north-western part where soft and fine-grained rock-types are common. We are confident that no
- 20 major events were missed due to lack of satellite data, because destroyed vegetation remains visible in the normalized difference vegetation index (NDVI), several years after large mass flows, e. g. about 10 years for the Kolka-Karmadon rock-ice avalanche. From the large number of detachments which occurred under very similar conditions we conclude that rising temperaturestotal). We conclude that high temperatures, combined with soft, fine-grained sedimentsare very critical components favouring, may increase the likelihood of mass wasting events and appear to be critical factors facilitating the detachment of entire valley

25 glaciers. The observed recurrence of mass wasting events make the Petra Pervogo range an potentially interesting candidate to witness glacier detachments by field studies.

#### 1 Introduction

#### 1.1 Glacier detachments

Glacier detachments, where a large volume of a valley glacier decouples from its bed and results in subsequent high-velocity

- 30 travel of the detached ice mass (Evans and Delaney, 2015), Glacier detachments are extremely rare and only a handful of them have been identified to date. Glacier detachments occur at a relatively low slopes around between events but the scientific understanding of these events is rapidly evolving. They occur when large volumes of glacier ice detach from valley glaciers with relatively low surface slopes (10° and to 20° and precursors show similarities to glacier surges where a glacier's velocity increases by one or two orders of magnitude (Quincey et al., 2011), however, without detachment. Glacier surges are favoured
- 35 by a climatic envelope and occur predominantly for rather long glaciers of low slope (Sevestre and Benn, 2015). In contrast to detachments, ice or glacier avalanches, originating from steep headwalls or hangingglaciers) and turn into highly mobile, ice-rich mass flows. Evans and Delaney (2015) list glacier detachments, together with ice avalanches, as one of three classes of catastrophic mass flows in glacierized mountain environments that are pertinent to this work. The classes are distinguished by their starting mechanism and the involved material. Both glacier detachments and ice avalanches mainly involve glacier
- 40 ice, but *ice avalanches* are much more frequent and typically originate from steep (hanging) glaciers. *Rock avalanches* with sometimes long runouts if they descend onto glaciers or snow covered terrain form a second class; the combination of the first two classes, or mass movements that involve both ice and rock (Evans and Delaney, 2015), are much more frequent. For both mass flowsclassified as ice-rock or *rock-ice avalanches*. For all three classes, potential energy is transformed into kinematic energy and into frictional heat. Frictional heat, and in additionally heating, and sometimes entrained sediments
- 45 (Moore, 2014, Sect. 5.2.2), increase the liquid water content and makes the which can enhance the mobility of the resulting mass flows , sometimes transformed to debris or mud flows, highly mobile (Schneider et al., 2011; Evans and Delaney, 2015; Davies, 1982). The high mobility leads to much longer run out distances than pure snow or runout distances compared to pure rock avalanches (Schneider et al., 2011), potentially reaching and in turn increases the potential for damage to inhabited areas (Petrakov et al., 2008).
- 50 Several past events including the 2002 Kolka-Karmadon rock-ice avalanche (Drobyshev, 2006; Huggel et al., 2005; Evans et al., 2009) , the 2016 Aru Co twin glacier collapse (Kääb et al., 2018; Gilbert et al., 2018), the 2013 and 2015 Flat Creek detachments (Jacquemart et al., 2020; Jacquemart and Loso, 2019), as well as comparable events reported from China and Argentina (Paul, 2019; Falasc , are well described by the definition of glacier detachments offered by Evans and Delaney (2015) because they involved "the decoupling of a glacier ice mass from its bed and catastrophic detachment of a large volume of a valley glacier". We therefore
- 55 adopt this term when documenting the newly discovered detachments, as well as when referring to events described elsewhere (e.g., Kolka-Karmadon detachment, Aru detachments).

The reasons for glacier detachments are not completely yet fully understood, but some several factors seem to play a major role: some detached glaciers presented Water has been found to be the main cause for the drastic reduction of basal friction that is key for a glacier detachment (Kääb et al., 2018; Gilbert et al., 2018; Jacquemart et al., 2020), but stress changes due to

- 60 loading from rock or rock-ice avalanches on the glaciers have also been invoked as possible triggers (Evans et al., 2009; Kääb et al., 2020) . Fine grained sediments or weak bedrock underlying the glaciers have been found for all glacier detachments, presumably facilitating the storage of large amounts of water leading to the necessary loss of friction (Kääb et al., 2018; Gilbert et al., 2018; Jacquemart . Also, ice-sediment mixtures have been shown to experience profound weakening at temperatures close to the melting point (Moore, 2014). In many cases, a close proximity to surging glaciers has been documented; in some cases, the detached glaciers
- 65 themselves exhibited a surge-like behaviour before detachment (Kääb et al., 2018) and one of the responsible mechanisms behind surgingappears to be increased water pressure which enhances basal sliding the detachment (Kääb et al., 2018), or had a prior history of surging.

Based on these observations, it has been hypothesized that glacier detachments may be catastrophic endmembers of the surging process (Kääb et al., 2018; Gilbert et al., 2018; Kääb et al., 2020). Glacier surges are rapid, transient, and often periodic

- 70 advances of a glacier that can last for weeks, months or even years Cuffey and Paterson (2010). Enhanced basal sliding, driven by increased subglacial water pressure, has been proposed as one of the key mechanisms behind surges (Kamb et al., 1985; Harrison and Post, 2003; Clarke et al., 2011). It Therefore, glacier detachments could be considered "runaway" surges. Up to now, no relation between surge activity and changing climate conditions has been found, but glacier surges are obviously favoured by an envelope of climatic conditions (Sevestre and Benn, 2015). Hence, it is suspected that elimate change increases
- 75 rising temperatures increase, at least temporarily, the amount of meltwater and may thus favour development of instabilities (Jacquemart et al., 2020). Another potential factor leading to instabilities are presumed to be soft bedrock lithologies for which ice-sediment mixtures which can show "profound weakening at temperatures closer to melting" (Moore, 2014). Soft sediments have been found for all of the probably best-studied events, the Kolka-Karmadon rock-ice avalanche (Drobyshev, 2006; Huggel et al., 2005; , the Aru Co twin glacier collapse (Kääb et al., 2018; Gilbert et al., 2018), and the Flat Creek detachments (Jacquemart et al., 2020; Jacquer
- Bo . Despite different terminology, all of these events would be classified as glacier detachments according to Evans and Delaney (2015)
   Together with comparable events reported from China and Argentina (Paul, 2019; Falaschi et al., 2019), these glacier detachments

The growing collection of documented glacier detachments raise the question of whether such events might be more common than previously thought, and whether they might happen more often considering rising global temperatures. While

- 85 similarities between pastevents have provided a baseline understanding of the conditions promoting, and factors triggering glacier detachments, their interactions and significance are still largely unknown. Yet precisely this understanding needs to be improved to provide a robust assessment of these hazards. how common such events really are, whether they occur more frequently compared to the past, or whether the increasing availability of satellite imagery simply causes an observation bias. The demonstrated importance of liquid water in the detachment process and the temporarily increasing availability of melt
- 90 water by rising global temperatures might be an evidence that such events occur more frequent.

The aim of this work is to provide an inventory of a series of glacier detachments and ice avalanches which glacier detachments, ice avalanches and rock-ice avalanches that occurred in the Petra Pervogo Range, Tajikistan, between 1973 and 2019. We use built the inventory by analyzing vast collections of satellite images, including the entire Landsat archive. We subsequently used this inventory to put the events glacier detachments in context with the local geology, elimatic conditions, climate conditions,

95 the regional distribution of surge-type glaciers, and individual glacier 's surging historypre-detachment glacier dynamics. To build the inventory we analyze a multiplicity of satellite imagery including the entire Landsat archive and investigated the usefulness of normalized difference vegetation index (NDVI) to detect glacier detachments retroactively, if they occurred during years with poor satellite coverageFinally, we also put these findings in context with glacier detachments known from elsewhere, in particular the well described events at Kolka, Aru and Flat Creek.

#### 100 2 Study site

The Petra Pervogo range (also called Peter the First or Peter the Great range) is situated in central Tajikistan, north-west of the Pamir mountain system. It extends to east to west for about 200 km between the Surkhob river to the north and the east with Moscow Peak (6785 m) as the highest peak and is bordered by the Surkhob and Obikhingou river to the north and south, both draining of which drain into the Vaksh river at the western end of the Petra Pervogo range. In the Western West Petra

105 Pervogo range, shown in Fig. 1, we identified four catchments which showed repeated large mass flows<del>resulting from glacier</del> detachments or rock/ice avalanches. Two detachments(, which happened in 2016 and 2017)-, were mentioned in (Dokukin et al., 2019) and on twitter Twitter (Dokukin, 2018). A third detachment(, which happened in 2019), was found during this study and independently by (Kääb, 2020)Kääb (2020).

To analyze recovery times of vegetation after large mass flows we compared the run out of the Kolka-Karmadon rock/ice 110 avalanche in the Caucasus (Russia) with the run out of two largest detachments in the Petra Pervogo range.

#### 2.1 Catchments in the Petra Pervogo range with large mass flows

In the catchment of the *Degilmoni Poyon* river (DP DP in Fig. 1) we identified a glacier detachment which occurred in 2019 (abbreviated as dp-19). It resulted in a mass-debris flow which almost reached the village Degilmoni Poyon, located 9 km downstream. The glacier detached between 2860 and 3360 meters altitude m asl (above sea level) at about 38.988° N, 70.694°

## 115 E.

In the catchment of the *Shuraki Kapali* river (*SK* SK in in Fig. 1), 13 km upstream of the village of Tojikobod (Tadzhikabad, 1737 inhabitants (Wikipedia, 2017), 1588 m a.s.l.), a series of detachments and ice avalanches occurred between 1973 and 2019, abbreviated as sk-*YY*. 2019. The nearby villages Kapali and Fathobod suffered from damage of infrastructure experienced some infrastructure damage from an event on 28 August 2016. The largest detachment from this catchment occurred in 2017

is (abbreviated as sk-17 - Ice masses detached in the following), when ice masses detached from between 3300 and of altitude 4000 m asl at about 38.974° N, 70.844° E.



Figure 1. West Petra Pervogo Range. Symbols  $\star$  indicates catchments where glacier detachments or ice avalanches mass flows occurred. Catchments are abbreviated by river names (DP, SK, Shi, Sha). Image contains modified Copernicus Sentinel-2 and MODIS data with borders, major rivers and place names added.

In a the catchment of the *Shikorchi* river (Shi in Fig. 1), we identified a series of mass flows between the years 2000 and 2017, most of them rock-ice avalanches originating at elevations between 3000 and 4000 m asl (39.026° N, 70.933° E).

In a side valley of the *Shaklysu* river (*Sha*), two large ice-rock avalanches , very likely detachments <u>Sha in in Fig. 1</u>).
 rock-ice avalanches occurred in 2006 and 2019. The debris flow resulting from the 2019 avalanche event traveled through the side valley and almost reached the Shaklysu river. The originated at altitude at Both events originated from a small glacier at 3800 m altitude (39.012° N, 70.998° E).

In the catchment of the *Shikorchi* river (*Shi*), a series of large avalanches (2000–2017), most of them rock-ice avalanches, was identified, originating between 3000 and altitude at (39.026° N, 70.933° E).

#### 130 2.2 Geology

The north west of the Pamir system shows a particulary high density of surging glaciers (Goerlich et al., 2020), spatially correlated with the occurrence of soft and fine-grained sediments like limestone, claystone, sanstone, conglomerates, aleurolite, gypsum and marl (see geological map by Ibrohim et al. (around 1974)). The Western western Petra Pervogo range is composed mainly of Cretaseous–Neogene sedimentary rocks. The catchments DP and SK are made up of redstone, aleurolite, claystone,

- 135 conglomerates and limestone. Striking erosional features and thick glacial debris cover support the fact that soft lithologies are widespreadin the Petra Pervogo Range. The Petra Pervogo range is located south of the Vakhsh thrust system and where shallow earthquakes in the upper 15 km of the crust are frequent (Schurr et al., 2014). <u>Similar sedimentary rocks are prolific</u> in the north-western corner of the Pamir mountains (lime-, clay-, and sandstones, as well as conglomerates, aleurolite, gypsum and marl; see geological map by Ibrohim et al. (around 1974)). The prevalence of such rocks, which may be easily erodible by
- 140 glaciers and freeze-thaw processes, is spatially correlated to the particularly high density of surging glaciers present in the area (Goerlich et al., 2020).

#### 2.3 Climateconditions

Two stations-meteorological stations, one located at Rasht/Garm (1316 m, 39.02°N, 70.37°E)and, 40 km west of SK in the Surkhob valley, and the other located above the Obikhingou river at Lyairun (2008 m, 38.89°N, 70.93°E), located in the valleys

145 of the Surkhob and Obikhingou river west and 12 km southeast of SK, indicate a mean annual precipitation of 700–1000 mm yr<sup>-1</sup> (Williams and Konovalov, 2008) and a mean annual air temperature (MAAT) of 10.7 °C and 7.1 °C, respectively, resulting in a temperature-lapse rate of -0.52 °C per 100 m. A temperature increase of over the last 40 years has been observed for the Pamir mountains, with an almost increase in fall and winter (Finaev et al., 2016).

For the vegetation covered avalanche run out zones of about we obtain a MAAT of which is comparable to the a MAAT of

- 150 at The zero-degree isoline in the run-out zone of the Kolka-Karmadon rock-ice avalanche at (Haeberli et al., 2004). At region is therefore at around 3300 mthe MAAT in the Petra Pervogo range is close to and Obu et al. (2019) indicates isolated patches of permafrost for the region., and a global permafrost map indicates that permafrost is patchy (Obu et al., 2019). Vegetation grows until about 3500 m and glacier tongues reach down to 2700–3200 m. Based on Sentinel-1 radar backscatter data we determined that snow melt at ~ 4000 m starts around mid April every year, and melting temperatures last until October. A
- 155 temperature increase of 0.42 °C over the last 40 years has been observed for the Pamir mountains, with an increase of almost 1 °C in fall and winter (Finaev et al., 2016).

#### **3** Data and methods

#### 3.1 Satellite data for event identification

As almost no in situ information is Very little in situ data was available to us, the study is mainly so this study is primarily 160 based on remote sensing data. To identifyand characterize detachments and ice avalanches we imagery. We combined optical and radar images, as well digital elevation models (DEMs) to identify, map, and characterize mass flows in the Petra Pervogo range as well as the distribution of surging glaciers in the range and the larger Pamir region.

#### 3.1 Detection and classification of mass flows

bands	band names	resolution
8-4-3	NIR-R-G	10 m( <del>ESA, 2015) and</del>
7-8+5-4	SWIR2-PAN+NIR-R	15m in the L8 panchromatic channel (USGS, 2013), were downloaded with the Sentinel EO I
3-2-1	NIR-R-G	15 images between 1986 and 1989. No imagery of L3 and L4 were available from our study s
7-8-3	SWIR2-PAN-R	<u>15, 30 m</u>
7-4-3	SWIR2-NIR-R	<u>30 m</u>
7-4-3	SWIR2-NIR-R	<u>30 m</u>
<u>4-3-2</u>	NIR2-NIR1-R	<u>80 m</u>
6-5-4	NIR1-R-G	<u>80 m</u>
6-5-4	NIR1-R-G	<u>80 m</u>
1	PAN	<u>2-12 m</u>
VV.	<u>VV</u>	<u>10 m</u>
1-2-3	<u>R-G-B</u>	<u>3 m</u>
	bands 8-4-3 7-8+5-4 3-2-1 7-8-3 7-4-3 7-4-3 4-3-2 6-5-4 6-5-4 6-5-4 1 VV 1-2-3	bands         band names           8-4-3         NIR-R-G           7-8+5-4         SWIR2-PAN+NIR-R           3-2-1         NIR-R-G           7-8+3         SWIR2-PAN-R           7-8-3         SWIR2-PAN-R           7-4-3         SWIR2-NIR-R           4-3-2         NIR2-NIR1-R           6-5-4         NIR1-R-G           1         PAN           VV         VV           1-2-3         R-G-B

Table 1. List of systematically analyzed (upper rows) and selected (lower rows) satellite imagery and image bands.

We analyzed the entire Landsat archive (L1-L8), all available Sentinel-2 (S2) images, the archive of ASTER imagery, and

- 165 selected Planet and reconnaissance Keyhole images. To characterize the events and to narrow down the event date we compared consecutive images. We also compared images from different years but acquired at the same month of the year. and ASTER archives, as well as all freely available reconnaissance Keyhole (KH3, KH-4A/4B, KH-9) images to identify, classify, and characterize large mass flow events in the glaciated environment of the western Petra Pervogo range (Fig. 1). A temporal overview of analyzed acquisitions is shown in Fig. 2.
- 170 S2 and L8 imagery, available since November 2015 and April 2013 at a resolutionof

For event detection, we searched for the abrupt disappearance of glaciers and also for the appearances of bright (ice rich) and dark (sediment rich) deposits in the valleys (for examples see Appendix). In addition, we looked for removal of vegetation, and changes in surface color indicating overtopping of landscape by debris flows. To detect such changes, we visually compared images from consecutive years but acquired during similar snow conditions at the same month (or day, if available) of each year.

- 175 For that we mainly analyzed imagery between July and Sept where snow and cloud cover was minimal and where vegetation showed a strong near-infrared (NIR) signal. In addition, we also compared consecutive images to detect events that occurred in winter or that did not leave traces visible to be detected in the next summer. We chose spectral bands by the best available resolution (Table 1), followed by their ability to discriminate vegetation, ice, rock and wet sediments. Where possible, we chose longer wavelengths which better penetrate aerosols. We used the moisture-sensitive short-wave infrared channel (SWIR2) to
- 180 distinguish wet and dry sediments (Kääb et al., 2014; USGS, 2020). To identify vegetation cover we used the NIR channel; For L7 we used the panchromatic (PAN) channel (L7) which covers the NIR spectrum, but provides a higher spatial resolution. For L8 we averaged the higher resolution panchromatic band 8 with the vegetation-sensitive NIR band 5. To identify snow and ice we used the red (R) or green (G) channel from the visible spectrum. ASTER imagery at resolution , available since



Figure 2. Temporal overview of analyzed satellite imagery. The barplot indicates the total number of available acquisitions per year.

September 2000, were also processed with the Google Earth Engine. We used the NIR, red, and green band (B3N, B2, B1).

- 185 To narrow down the occurrence of avalanches date of events we also analyzed selected optical Planet imagery and Sentinel-1 (S1) radar imagery. As earliest images, we analyzed declassified panchromatic satellite images from the Keyhole missions (KH-3 and KH-7), dating back to 1961 and 1973, with resolutions between 7 and 10 m (USGS, 2008). The images were not orthorectified. We analyzed all images at a scale of approximately 1:25'000. For a more detailed analysis of detected events we zoomed in. We considered only events where horizontal length from release area to deposit end exceeded about 2 km. Due
- 190 to the growing availability of imagery (see Fig. 2) our collected dataset is very likely biased towards more recent years. As glacier detachments are extremely rare events, we aimed for detection of as many as possibly events, rather than on temporal consistency of the dataset as done by others (e.g. Bessette-Kirton and Coe, 2020).

#### 3.2 Avalanche characterization

To characterize detachments and ice avalanches, we measured the horizontal avalanche path length, the total fall height, the 195 maximum height of

Determining the nature of the detected events is rarely a straight forward task, but we try to offer our best assessments based on the following criteria:

- Glacier detachment (d): A glacier was visible prior to the event and lies within a GLIMS inventory (Glacier Land Ice Measurements from Space) polygon; the glaciers were located at the bottom of a valley or in topographical depressions;
- 200 exposed bedrock or shadows indicated the removal of large amounts of ice; downstream deposits consisted of mostly ice.

## Table 2. List of available and generated DEMs.

DEM name	Acquisition date or period	coverage
SRTM	11-02-2000-22-02-2000	full
ALOS W3D	2008-2010 (2006-2011)	full
TanDEM-X	2011-03-09-2014-12-01	partial
TanDEM-X	2018-08-31, 2018-09-11	partial
WorldView	2018-09-09, 2019-08-03, 2020-04-10	partial

- Ice avalanche (i): Only small amounts of ice were removed and the glacier seemed mostly intact; downstream deposits consisted of mostly ice.
- Rock-ice avalanche (r/i): Release area included likely some ice but also rock; deposits were mostly ice free.
- 205 Rock avalanche (r): Release area included mainly rock; deposits were mostly ice free.

#### 3.2 Mass flow descriptions

For each detected event, we determined the release area and the slope of the release zone. To characterize the mobility of the mass flows, we determined the angle of reach  $\alpha$ , calculated by  $\tan \alpha = H/L$  from the avalanche trim lines, and the maximum width of the avalanches with the Google Earth Pro measuring tool (elevation information based on the SRTM). To calculated

- 210 the impacted area we mapped the total avalanche run out zone from satellite imagery with the software QGIS. The horizontal avalanche path length and fall height were horizontal path length L and the total fall height H measured from the avalanche crown or rupture line (Schweizer et al., 2003), top of the release area to the lowest avalanche runout point. To assess the mobility of the mass movements, we calculated the mobility index point of the runout. The angle of reach (or mobility index or *Fahrböschung*, also known as the *angle of reach*  $\alpha$  resulting from the ratio of total fall height and horizontal runout distance,
- 215  $\tan \alpha = H/L$  which) corresponds to the average friction coefficient (Scheidegger, 1973) of the mass flow (Scheidegger, 1973) . We also measured the total impact area and the maximum height of the flows' trim lines using the elevation information of the SRTM DEM embedded in Google Earth Pro. Snow avalanches have a typical Fahrböschung of 20–40° and debris flowsbetween 10 and 20° (McClung and Gauer, 2018; Lied and Toppe, 1989; Prochaska et al., 2008).

#### 3.3 Detachment volume estimation

- 220 To estimate the detached volume of the dp-19 event we obtained Precise estimation of volume changes requires the availability of timely elevation models before and after an event. Unfortunately, this was only the case for the event dp-19, for which three pairs of World View stereo images (09 September 2018, 03 August 2019, and 10 April 2020; Neigh et al. (2013) ) which, unfortunately, covered only the DP catchment. DEMs were generated using SETSM (Noh and Howat, 2017) and were coregistered (Neigh et al., 2013) could be processed into DEMs using the SETSM algorithm (Surface Extraction with
- 225 TIN-based Search-space Minimization from Noh and Howat (2017)). We coregistered the DEMs to each other following Nuth

and Kääb (2011). Since the glacier detachment sk-17 showed a similar geometry and area as the dp-19 event, we assume the same ice thickness to estimated the volume of the detached area but estimated an additional error of 20%.

In the SK eatchment, For all other detected events, the DEM difference between the C-band SRTM (Farr et al., 2007) and the ALOS World DEM 3D (W3D) (Tadono et al., 2016) revealed a previously unknown event and the two DEMs were used

230 to roughly estimate its volume . The event was constrained by satellite imagery to at least two events in 2003 and 2006 (abbreviated sk-03+06). available DEMs (Table 2) had either no precise time stamp or the detected events happened several years before or after the DEM acquisition, inhibiting precise volume estimates. In some cases, however, the DEM time series provided insight into a glacier's dynamics prior to the events.

Volume uncertainties associated with all DEM differences were estimated follow the method described in (Miles et al., 2018)

235 . To get a reliable estimate of uncertainty from-

To estimate the uncertainties of the volume estimates we masked all areas impacted by the events and tiled the DEMs into  $n^2$  tiles (n ranging from 2 to 200). By calculating the median height change (dH) per tile and relating this to tile size, we get estimates of the average per-area dH error (Miles et al., 2018). This empirical error metric accounts for all error sources, including differences in snow cover, processing errors etc. In the World View images , we masked obvious clouds (large areas

with a DEM difference beyond  $\pm 130 \text{ m}$ ) before performing the uncertainty assessment in addition to the area impacted by the glacier detachment.

#### 3.3 Glacier velocity prior to detachmentPre-event glacier dynamics

To identify detachment-precursors like increased sliding or strong crevassing on the glaciers before the two largest detachments (sk-17, dp-19) we Several studies have described surge-like behavior, increasing flow velocities, or opening crevasses prior

245 to glacier detachments and ice avalanches (Kääb et al., 2018; Jacquemart et al., 2020; Faillettaz et al., 2011). Where the data permitted, we tried to detect and describe such behavior.

We used high resolution S2 and L8 imagery - Velocities immediately before detachment to measure flow velocities and crevasse opening prior to the events sk-17 and dp-19. Velocities were determined by manual tracking of surface features and by measuring the width of the opening rupture line.

#### 250 3.4 Surge history of detached glaciers

To study the surge-history of the detached glaciers we used lines. We also tracked any surging or surge like mass redistribution using DEMs from SRTM, TanDEM-X (TDM), the <u>ALOS World DEM 3D (W3D)</u>, and World View (WV) stereo imagery (Farr et al., 2007; Krieger et al., 2007; Tadono et al., 2016; Neigh et al., 2013; Noh and Howat, 2017). We analyzed six interferometric TDM pairs acquired between 03 May 2011 and 05 September 2014, and processed DEMs as outlined in (?) to

255 calculate generated DEMs using the InSAR processing algorithm detailed in (Leinss and Bernhard, 2021) to derive the surface dynamics from DEM differences.

#### 3.4 Meteorological Regional surge patterns

To compare the geometric characteristics of detected glacier instabilities within a wider regional context, we mapped glacier surges in the entire Pamir mountains, that occurred between 2000 to 2011 by differencing the C-band SRTM and the optical

- W3D, both at 30 m resolution, horizontally aligned following Nuth and Kääb (2011). We analyzed DEMs from 37–39 North and 67–75 East. For the SRTM DEM an absolute vertical accuracy of 6 m is given in (Farr et al., 2007) but the C-Band radar can penetrate up to 10m into dry snow and firn (Rignot et al., 2001). For the W3D a vertical accuracy of 5 m is given (Tadono et al., 2016). Imagery for the W3D was acquired between 2006 and seismic dataTo analyze climatic influences we used data from the two meteorological station Garm and Lyairun available from 1961–1990 and ERA-Land reanalysis data from
- 265 1981–2019 obtained for the coordinate 70.90°E, 38.95°N (), south east the SK catchment. To obtain homogeneous temperatures time series we calculated the mean difference between 2011, but the main acquisition period for the Petra Pervogo range was between March 2008 and March 2011.

For mapping of glacier surges, we considered glaciers as beeing an active surge phase when the glacier showed a surface height increase of more than 10 m over the glacier tongue accompanied by surface lowering further upstream. We consider

- 270 glaciers being in a quiescent surge phase when surface lowering over the glacier tongue exceeded 10 m and a significant surface height increase was visible upstream, in a possible reservoir area. To determine the slope of the Lyairun and ERA-Land temperature and shifted the data of the Lyairun station by , in agreement with a lapse rate of per . ERA-Land precipitation required a scaling factor of 16.7 to match data from the Lyairun station. surging part of a glacier we measured the horizontal length and the elevation difference of the area that showed the surge-like (wave-like) elevation change pattern.
- 275 To assess earth quakes as triggering factors, we used data of seismic events which occurred within a range of about around the Petra Pervogo range. The data was provided by the USGS via the IRIS Data Management Center.

#### 3.5 DEM differences for detection of surging glaciersMeteorological and seismic data

To analyze climatic influences on glacier detachments and ice/rock-ice avalanches, we used data from the two meteorological stations Garm and Lyairun, available from 1961–1990, and ERA-Land reanalysis data from 1981–2019 (Copernicus Climate Change Service)

280 . ERA data was obtained for the coordinate 70.90°E, 38.95°N, 6 km south east the Shuraki Kapali (SK) catchment, and the height 3470 m a.s.l.. To obtain homogeneous temperature time series we calculated the mean difference between the Lyairun and ERA-Land temperature and shifted the temperature data of the Lyairun station by +7.6 °C to match the ERA-Land temperature data used for analysis. The shift is in agreement with a lapse rate of 0.52 °C per 100 m. ERA-Land precipitation required a scaling factor of 16.7 to match data from the Lyairun station.

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Sketch of measured parameters for surging glaciers.

To put the detachments and mass movements into a regional context, we mapped surging glaciers in the entire Pamir mountains from 2000 to 2011 by differencing the C-band SRTM and the optical W3D, horizontally aligned following Nuth and Kääb (2011) . We analyzed DEMs from 37–39 North and 67–75 East. The SRTM DEM was acquired in February 2000 and is available at 1 arcsec resolution (30 m) from the USGS.An absolute vertical accuracy of 6 m is given in (Farr et al., 2007) but the C-Band

**Table 3.** Characteristics Type and characteristics of glacier detachments detected mass flows determined as described in Sect. 3.1 and other events 3.2. Empty spaces fields indicate unknown quantities , dashes indicate quantities without meaningthat could not be determined. Surge-like instabilities were observed several years before the sk-17 and dp-19 events ("yes" in paranthesis) but not immediately before the detachment. \*The The sk-16b event transformed into a debris flow, possibly after entrainment of entraining material of left by the sk-16a event. Due to lack of data we could not determine which fraction of the total length of belongs to the initial ice avalanche and and which to the subsequent mud flow.

Event abbreviation	<del>sk-73</del> dp-19	<u>sk-73</u>	<u>sk-94</u>	sk-03 <mark>+06</mark>	$\underline{sk-04}$	<del>sk-04</del> sk-06	<u>_sk-10</u>
Release area Type of mass flow	ď	r⁄i	r/i	<u>d</u>	d	į	<u>r/i</u>
Sub-catchment	<del>detach</del>	detach_east	ice-west	detach(?) center	detach-west	ice/rock_center	detach w
Area Release area $(10^3 \text{ m}^2)$	244	220	<del>243 <u>53</u></del>	<del>75</del> -1 <u>90</u>	<del>95_85</del>	55	120
Volume Release volume $(10^6 \text{ m}^3)$	$3.2 \pm 0.3 8.8 \pm 2.7 8.6 \pm 0.9$			$\geq 2.9 \pm 0.3$	-	-Horiz. length (m)	<del>1050</del>
Slope Release slope (°)	18.7	18.5	<del>22.1</del> -20.8	18.3	19.8	<del>24.4-</del> <u>26.6</u>	20.5
Surge observed	(yes)		<del>no-</del>	<del>no-</del>	no	<del>(yes)</del>	
Size Impacted area (km <sup>2</sup> )	1.83	0.71	0.76	1.17 <del>,0.50</del> -	0.42	0.50	0.62
Horiz. path length (km)	<del>3.34 <u>6.7</u></del>	3.3	2.7	7.3 <del>, 3.4</del>	2.9	<del>5.4</del> - <u>3.4</u>	3.0
Height difference (m)	1525	830	<u>750</u>	1520 <del>, <mark>850</mark></del> -	790	<del>1200_850</del>	800
Angle of reach $\alpha$ (°)	12.8	14.0	15.5	11.8 <del>, 14.0</del>	15.2	<del>12.4</del> - <u>14.0</u>	14.9
Max trim line height (m)	168						
Figure reference	3,4	A2	<b>??a</b> ,A3b	A5a	A3c	.A5b	<b>??</b> A4

- 290 radar can penetrate up to 10m into dry snow and firn (Rignot et al., 2001).Imagery for the W3D was acquired between 2006 and 2011 (main acquisition phase between March 2008 and March 2011 in the Petra Pervogo range) therefore no precise time stamp is available. The W3D is commercially available at resolution and has a vertical accuracy is of 5 m (Tadono et al., 2016) . Here we used the freely available version. To assess earthquakes as triggering factors, we used data of seismic events that occurred within a range of about 100 km around the Petra Pervogo range. We selected the earthquakes which occurred within
- 295 the time period given by a pre-event satellite image and a post-event image. To capture delayed triggering by earthquakes we also selected earth quakes up to two days before acquisition of the pre-event image. Then we assessed the earthquakes's magnitude and the distance to the catchments where mass flows were detected and compared the earthquake's distance and magnitude to the threshold for triggering of disrupted landslides according to (Jibson, 2013).
- We considered a glacier beeing in its active surge phase when the glacier showed a surface height increase of more than over 300 the glacier tongue accompanied by surface lowering further upstream. We consider glaciers being in a quiescent surge phase when surface lowering over the glacier tongue exceeded 10 m and a significant surface height increase was visible upstream, in a possible reservoir area. To determine the slope of the surging part of a glacier we measured the horizontal length and the elevation difference of the surge-like elevation change pattern as illustrated in Fig. ??.

 Sect. 3.1.
 Referred figures show images with the best visibility of the events; shown images do not necessarily agree with they can differ from the images used to that limit the date of occurrence.

Event	type	pre-event image	post-event image	shown in
dp-19	d	2019-08-02, S2	2019-08-03, L8	Fig. <u>3,</u> 4
sk-73	<mark>∉-r/i</mark>	<u>→ 1973, KH-</u> 1971-09-15, KH-4B	1973-08-03, <del>KH-KH-9</del>	Fig. A2
<u>sk-94</u>	r/i	<u>1994-07-06, L5</u>	<u>1994-07-22, L5</u>	Fig. A3b
sk-03	d	2003-08-24, L7	2003-09-25, Aster	Fig. <mark>??</mark> A5a
sk-04	d	2004-09-02, L7	2004-09-18, Aster	Fig. <del>??aA3c</del>
sk-06	<del>d(?) i</del>	2006-08-23, L7	2006-09-01, L7	Fig. <mark>??</mark> A5b
<del>sk-16a <u>s</u>k-10</del>	<u>r∕i</u>	<u>2010-08-27, L7</u>	2010-09-04, L5	Fig. A4a
<u>sk-16a</u>	$\overset{d}{\sim}$	2016-07-14, S1	2016-07-25, L8	Fig. <del>??A5</del> c
sk-16b	<del>d(?)_r/i</del>	2016-08-27, L7	2016-08-31, S1	Fig. <del>??A</del> 4b
sk-17	d	2017-07-10, Planet <del>(?)</del>	2017-07-11, S2	Fig. 5
sk-19	<mark>r∕i /</mark> r	2019-06-21, S2	2019-06-23, S1	Fig. <del>??A</del> 4c
<del>sha-06 s<u>hi-01</u></del>	<mark>d−r</mark> _	<del>2006-08-16</del> 2001-03-11, L7	<del>2006-09-01</del> 2001-03-18, L7	Fig. <del>8d</del> A6a
<del>sha-19 shi-09</del>	<del>d-r</del> _	2019-07-06, Planet(?) 2009-04-09, L7	<del>2019-07-08</del> 2009-05-11, L7	Fig. A6d
<u>shi-17-1</u>	$\stackrel{r}{\sim}$	2017-06-02, L7	<u>2017-06-03,</u> L8	Fig. <mark>&amp;A6</mark> b
<del>shi-01_shi-17-2</del>	r <del>/i</del> -	<del>2001-03-11, L7</del> -2017-06-18, L8	<del>2001-03-18, L7</del> -2017-06-21, S2	Fig. <del>??aA6c</del>
<del>shi-09_</del> sha-06_	r/i	<del>2009-04-09</del> 2006-08-16, L7	<del>2009-05-11</del> 2006-08-23, L7	Fig. <del>??c</del> 8d
<del>shi-17_</del> sha-19	r/i	<del>2017-06-01</del> 2019-07-06, S2	<del>2017-06-08</del> 2019-07-08, S2	Fig. <mark>??8</mark> b

#### 3.6 NDVI for mass flow recognition and vegetation recovery analysis

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The older, available imagery showed gaps of a few years in which detachments mass wasting events could have happened without being noticed. However, mass flows events with long runouts may remove or bury vegetation which can take years to recover. To assess recovery times vegetation recovery times, and to estimate how likely large events might have been unnoticed in post-event imagery containing a vegetation sensitive channel, we analyzed time series of the NDVI = (NIR - Red)(NIR + Red) NDVI = (1 the band combinations (B5, B4) and (B8, B4) for LS8 and S2, respectively, of the two recent detachments, dp-19, and sk-17.

S2 false color imagery capturing the evolution of the detachment dp-19. From (a) to (b) increased crevassing is visible. (c) shows the detached glacier, (d) the run out zone of the resulting avalanche. (a-c) Copernicus Sentinel data (2019). (d) Google Maxar Technologies. DEM differences of the detachment dp-19. (a): WorldView elevation differences from before and after the event reveal a detached volume of  $8.6 \times 10^6 \text{ m}^3$ ; 2020, DigitalGlobe; NextView License. (b, c) DEM differences indicate

We compare the results with vegetation recovery in the run out run out

315 a surge-like elevation change pattern after 2000 which continued at least until 2013. (d) In 2007 strong crevassing resemble surge-like dynamics (Google, Maxar Technologies).

#### 4 Results

Our analyses revealed a very high activity of mass wasting events in the western Petra Pervogo range. In particular, we have detected two large-volume glacier detachments, as well as several smaller glacier detachments, ice avalanches and rock-ice

320 <u>avalanches</u>. Table 3 summarizes the characteristics of the detected events and all detected events; Table 4 lists satellite images used to narrow down their date of occurrence. The following two sections describe the events in detailmain detachment events, followed by short descriptions of all other events grouped by (sub)catchments.

#### 4.1 2019 Degilmoni Poyon (DP) glacier detachment 2019(dp-19)

In the DP catchment we identified a valley glacier which detached between 02.08.2019 and 03.08.2019 (Fig. 3). A valley glacier in the Degilmoni Poyon catchment detached between 02 and 03 August 2019. The glacier is listed in the GLIMS data base with the ID G070689E38981N (Raup et al., 2007) and its outline comprises a headwall with hanging ice and a glacier which feeds from the headwallsteep, ice-covered headwall and a lower-angle valley glacier below. The detachment , abbreviated as dp-19, involved essentially the entire glacier below the headwall -(Fig. 3a-c).

- From the difference of two WorldView DEMs from 2018 and 2019, shown in Fig. 4a, we determined a detached area of approximately  $244 \times 10^3$  m<sup>2</sup> and a detached volume of  $8.59 \pm 0.88 \times 10^6$  m<sup>3</sup>. A cloud obscured a small part of the detachment area in the 2019 image, but the DEM difference between a 2020 and the 2018 DEM indicated that only a minimal negligible part of the detachment area is was obscured. The post-detachment glacier bed showed a nearly triangular cross section, with a maximum erosion depth of 91 m (mean depth: 35 m). The detached mass travelled 6.7 km down the valley, with an elevation loss of 1525 m, resulting in a an angle of reach of  $\alpha = 12.8^{\circ}$ . After traveling 4.3 km down valley, the avalanche trim line
- 335 continuous trim line of the mass flow reached over 150 m above the valley in a curve indicating a very high velocity (arrows in Fig. 3d). The avalanche stopped 2.4 km later, reaching it's end approximately only 2.6 km before outside the village Degilmoni Poyon.

DEM differences prior to the detachment(Fig. 4b, c) indicate that the glacier surged between 2000 (SRTM) and 2006–2011 (W3D). L7 imagery indicates an Prior to its detachment, dp-19 had an active surge history. L5 imagery indicate a surge-like

- 340 advance of about 230 m between 1991 and 1995. The glacier advanced again by about 100 m between 1999 and 2003, followed by quiescence until until 2006. DEM differences between 2000 (SRTM) and 2006–2011 (W3D) indicate a surge-like mass redistribution during the advance (Fig. 4b,c). In a Google Earth Pro-image from 30.07.2007 the glacier appears heavily crevassed (Fig. 4d), indicating an active surge phase another active phase of advance which last until at least 2008 according to L7 imagery. It advanced again by about in total until 2013. After that, the glacier entered a pre-detachment quiescent phase.
- 345 In L7, L8, and S2 data that glacier appears progressively sediment covered and no special activity was detected between 2008 and 2019. TanDEM-X data from 03 May 2011 and 21 February 2013 (Fig. 4c) indicate an elevation loss of about over the



Figure 3. S2 false color imagery capturing the evolution of the detachment dp-19. From (a) to (b) crevasses open around the glacier outline (arrows) while the middle part of the glacier remains snow covered. (c) exposed glacier bed after detachment, (d) runout zone of the resulting debris flow; arrows indicate the maximum height of the trim line. (a-c) Copernicus Sentinel data (2019). (d) ©Google, Maxar Technologies.



**Figure 4.** DEM differences of the detachment dp-19. (a): WorldView elevation differences from before and after the event reveal a detached volume of  $8.6 \times 10^6 \text{ m}^3$ . The shown area corresponds to the white frame indicated in Fig. 3a. (b, c) DEM differences indicate a surge-like elevation change pattern after 2000 which continued at least until 2013. (d) In 2007 strong crevassing at the glacier outline resemble surge-like dynamics. (a) 2020, DigitalGlobe; NextView License, (c) ©Google, Maxar Technologies.

later detached area. In the following years, satellite imagery suggests healing of the crevasses and no detachment or avalanche could be found between 2007 and 2019. Between 2013 and 2018 satellite imagery, and DEM differencing indicates melt and retreat of the previously advanced tongue. Only about 10–15 m. All datasets indicate that the glacier's slow retreat and melt continued until shortly before the detachment. About three weeks prior to the detachment, around 11 July 2019, the bergschrund

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had Bergschrund started widening by  $1 \text{ m d}^{-1}$  and we observed increased sliding leading and enhanced to enhanced lateral crevassing around the detached area. In the middle part of the glacier, we did not observe any new crevasses exposed by snow melt indicating that the lateral crevasses are caused by the progressive detachment of the glacier body.

Erosion Pre-event imagery, lasting back to an KH image from 1961, show erosion patterns and missing vegetation, matching surprisingly well the avalanche flow patterns shown in Fig. 3dare visible in Google Earth imagery and already in an KH image

355 surprisingly well the avalanche flow patterns shown in Fig. 3dare visible in Google Earth imagery and already in an KH image from 1961 but. However, we could not find any confirmation of an earlier avalanche. large mass flow before the 2019 event. Shuraki Kapali catchment area and location released ice masses (color). Polygons in magenta correspond to the outlines of the GLIMS database, black dotted lines mark terrain ridges. Map data: image from 19 July 2019 by Google, CNES/Airbus, 2020.

## 360 4.2 Shuraki Kapali (SK)

In the upper catchment of the Shuraki Kapali river, for which the GLIMS database lists five small glaciers, we identified a series of glacier detachment and several other mass flows which could not clearly be identified. Fig. 7 shows the locations of the released masses (in color) and GLIMS glacier outlines in magenta. About three kilometers downstream of the headwall, a glacier which has surged in 2010/11 enters the catchment area from the west.

#### 365 4.1.1 Shuraki Kapali glacier detachment 2017

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## 4.2 2017 Shuraki Kapali glacier detachment (sk-17)

Another large-volume glacier detachment was reported in this the Shuraki Kapali catchment by Dokukin et al. (2019). Between 10 and 11 July 2017, almost the entire valley glacier (GLIMS ID G070852E38974N) with an area of about  $250 \times 10^3 \text{ m}^2$ 

370 detached (Fig. 5). Based on the mean-Because the geometry of sk-17 is remarkably similar to that of dp-19, we assumed the same mean detachment depth of 35 m of dp-19, we estimated to estimate a volume of  $8.8 \pm 2.7 \times 10^6$  m<sup>3</sup>. The detached mass lost 1520 m in elevation while travelling 8.5 km down the valley, which corresponds corresponding to an angle of reach of  $\alpha = 10.1^{\circ}$ .

Figs. 5(a-c) show the evolution of the glacier prior to the detachment. Some crevassing, unusual compared to previous years,
 becomes Crevasses, surrounding the detaching area, become increasingly visible 60 days before the detachment, and heavy crevassing indicative of enhanced sliding is visible indicate enhanced sliding 20 days before the detachment. Manual tracking of surface features in an S2 image pair from 21 and 28 June 2017 indicates a sliding velocity of about 3 m d<sup>-1</sup>. Two weeks later, the glacier detached.

DEM differences prior to the detachment indicate a surge-like elevation change between 2000 and 2006–2011 (Fig. 6a) which continued until 2011 (TDM). However, prior to the detachment the glacier's surface elevation seems nearly stagnant,



Figure 5. S2 false color imagery capturing the evolution of the detachment sk-17. Copernicus Sentinel data (2017).



**Figure 6.** Shurali Kapali catchment. (a) the W3D-SRTM-DEM difference W3D - SRTM shows a clear height loss due to detachment sk-03+06 (red) where the detachment sk-03 and a the ice avalanche sk-06 occurred. A surge-like elevation gain (blue) is visible at the glacier tongue of sk-17 which detached in 2017 (bluesk-17). (b) the TDM DEM difference between 2011 and 2014 shows hardly any surging a nearly stagnant surface height before the sk-17 event; some ice is moving into. At the sk-03+06 detachment area and a strong elevation loss can be seen at the confluence of the 2010/11 surge and the valley floor, likely due to elevation loss indicates melt of ice and previous mass flow deposits. (c) shows the possible rupture line of sk-03 or and sk-06 ; events (d) suspected end of the sk-03 avalanche indicated by existing tall vegetation at the valley floor (arrow). Imagery in (c) and (d) ; @Google, Maxar Technologies.

and TDM DEM differencesshow hardly any advance between 2011–2014, Fig. 6b, and show hardly any change in surface height between 2011–2014. TDM and L8 imagery don't show any advance or retreat either.

For the same glacier, we found evidence for an earlier detachment, sk-73, in a Keyhole (KH) image from 03 August 1973, shown in Fig. A2b. From the run-out distance of and the estimated height difference we obtain an angle of reach of around 14°.

385 This is considerably lower than usual for snow avalanches (20–40°) (McClung and Gauer, 2018) and resembles a similar angle of reach as obtained for the two detachments dp-19 and sk-17 (Table 3). Avalanche-like deposit pattern in an earlier KH image from 30 August 1961, Fig. A2a, and widening of the valley until 1973 indicate that large mass flows have occurred already before and have filled the valley before the 1973 ice avalanche occurred.

#### 4.3 Other events

#### 390 4.3.1 Shuraki Kapali (SKevents in 2003, 2006, 2016) catchment

In the height difference between the SRTM and the W3D, red in Fig. 6a, we found a height loss of up to (on average), indicated by "sk-03+06". The same area is shown in in Fig. 7 (dark blue outline) and is located on a glacier listed with the ID G070846E38972N in the GLIMS data base. From satellite imagery and DEM differences we estimate an approximate area of and a volume loss of . A possible rupture line is visible on a Google Earth image from 13 August 2008 (Fig. 6c).

In 2016 another ice avalanche originated from the same area (sk-16a, orange in The Shuraki Kapali catchment appears to be a hotspot for glacier detachments and ice or rock-ice avalanches. Distributed across three small sub-catchments, the GLIMS database lists five small glaciers in the upper part of this drainage (Fig. 7), also mentioned by Dokukin et al. (2019). The avalanche occurred between 14 and 25 July 2016, Fig. ??e, travelled over a height loss of , corresponding to an angle of reach of 12.4°. TDM imagery and DEM differences indicate that the sk-03+06 area has partially filled up with ice... We briefly describe the detected events, grouped into their respective sub-catchments, from west to east.

## 4.4 SK events in 2004, 2016, 2019

In the western part of the SK catchment area In the *western part* of the Shuraki Kapali catchment the GLIMS data base lists two small glaciers from which three ice avalanches at least five mass flows originated. Extensive debris cover on the glacier two glaciers made a precise delineation of the detached areas difficult.

405 Between 02 and 18 September 2004 the lower parts and unambiguous classification of the events difficult.

- In July 1994 the lower part of a glacier with the GLIMS ID G070839E38975N detached (sk-04broke away (sk-94) and resulted in an ice rock-ice avalanche with an approximate run out distance of runout distance of 2.7 km. We did not find earlier events in this catchment but KH imagery indicate strong erosion and sediments below the glacier (Fig. A3a).
- In September 2004 a slightly larger part detached from the same glacier (sk-04) and resulted in a mass flow with an approximate runout distance of 2.9 km. The detachment zone and the avalanche are visible in Fig. **??a**A3c. Additional

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An inspection of satellite imagery revealed that at least two ice avalanches are responsible for the visible height loss. One occurred between 24 August and 25 September 2003 (sk-03) with a runout distance of about , Fig. ??a, while loosing 1520 meters in altitude, corresponding to an angle of reach of 11.8°. The run-out is clearly visible in Aster imagery (inset in Fig. ??a) and matches with missing vegetation on the valley floor in Fig. 6d. The comparison of two L7 image from August 2003 and 2004 reveals the detached area (white rectangles in Fig. ??a). The other event occurred between 23 August and 01 September 2006 (sk-06) and had a runout of 3.4 km, Fig. ??b. Though the avalanche is clearly visible on L7 imagery, we could not identify the exact release area and can therefore not classify it unambiguously as detachment.-

Figure 7. All release areas of ice masses in the Shuraki Kapali catchment overlap with the glacier outlines (gray shading) of the GLIMS database. Black dotted lines mark terrain ridges and separate sub-catchments. Background image from 19 July 2019 ©Google, Maxar Technologies.

ice fell off the from the upper scarp of the detachment zone a few days later at the location indicated by the (arrow in the inset of Fig. ??a A3c) resulting in a similar runout distance of 2.5 km.

Local media report a mud-flow which occurred on-

- In early September 2010 ice continued to break off from the remaining parts of the glacier and resulted in a rock-ice avalanche (sk-10).
- For 28 August 2016, local media reported a mud-flow as a result of glacier break off (Tajik telegraph agency, 2016; Radio Ozodi, 2016). Based on satellite imagery we We determined a glacier area of 160 × 10<sup>3</sup> m<sup>2</sup>, indicated as sk-16b in Fig. 7, which detached, corresponding to the major part of the glacier with the GLIMS ID G070835E38972N which is located above the glacier where previous events (sk-94, sk-04, sk-10) happened. The detachment scarp and the avalanche trim line are indicated by an arrow and a white dotted line in Fig. ??A4b. The avalanche reached or run over the deposits of the sk-16a event (see below) and transformed into a debris-flow of a remarkable runout distance of 19.1 km (measured from the detachment scarp) resulting in a very low angle of reach of only 7.7°. The avalanche passed villages of Fathobod and Kapali, Fig. 1, where ten buildings and a bridge were damaged or destroyed and several cattle were swept away. The mud-flow reached the Surkhob River at 1507 m of altitude (inset in Fig. ??A4b), still containing pieces of ice according to photographs in media, and blocked temporarily the Shuraki Kapali river (Radio Ozodi, 2016). The total path length of is the combined length of the glacier detachment and the debris flow.
  - Between 21 and 23 June 2019 an ice avalanche (sk-19a rock-ice avalanche (sk-19) was released from the same area at the same place as sk-16b, followed by one or two minor. However, Google Earth imagery indicates that a deeper layer of rock or ice has detached. The event was followed by a minor ice avalanches between 26 June and 01 July 2019 as shown in visible in the center of the sk-19 deposits, Fig. **??**A4c. The run out runout distance of the main avalanche mass flow is approximately 9 km with an angle of reach of 12.1°. In total an area of approximately detached, however, neither a clear rupture line could be identified nor a glacier was visible on this location because of very strong sediment coverage. Still, the location is listed as  $150 \times 10^3$  m<sup>2</sup> detached from the mountain.

In the *central part* of the Shuraki Kapali catchment the GLIPS data base lists a glacier with the ID G070839E38975N in 435 the GLIMS data base. G070846E38972N. Here, we identified three events, two glacier detachments, one followed by an ice avalanche.

- In September 2003 the lower part of the glacier detached (sk-03) and ran out for about 7.3 km, resulting in an angle of reach of 11.8°. The runout is clearly visible in Aster imagery (inset in Fig. A5a) and matches with missing vegetation at the valley floor shown in Fig. 6d. The detachment area of  $170 \times 10^3 \text{ m}^2$  was derived from L7 imagery one year after detachment (Fig. A5a). In the detachment area, DEM difference between the SRTM and the W3D showed a height loss of up to 40 m (15 m on average; red area in Fig. 6). From DEM differences we estimate a volume loss of at least  $2.9 \pm 0.3 \times 10^6 \text{ m}^3$  for sk-03. The volume is very likely larger because the W3D is mainly composed from data acquired several years after the event, between 2006 and 2011.

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#### 4.3.1 Detachment 2019 near the Shaklysu river

- 445 In a side-valley of the Shaklysu river a large avalanche occurred between 06 and 08 July 2019, originating from the upper reaches of a very small glacier with the GLIMS ID G070995E39014N at . Exposed rocks at the former location of the glacier in Google Earth imagery indicate that the entire glacier has detached (
  - In late August 2006 glacier ice with an area of  $55 \times 10^3 \text{ m}^2$  (sk-06) was release just above the detachment scarp of the sk-03 event, resulting in a runout of 3.4 km, Fig. A5b. The likely rupture line of this event, and the detached area of sk-03 below, is visible in a Google Earth image from 13 August 2008 (Fig. 6c).
  - In July 2016 another detachment, mentioned by Dokukin et al. (2019), originated from the same area (sk-16a, Fig. 8A5c). The resulting avalanche travelled over a vertical distance of with mass flow travelled 5.6 km over a height loss of 1200 m, corresponding to an angle of reach of 15.812.4° and almost reached the Shaklysu river. No volume was estimated for this event . A maximum trim line height of indicates a high avalanche velocity.Satellite imagery indicate that the glacier was not existent in 2013 but build up mass until detachmentin 2019. TDM imagery and DEM differences indicate that the valley exposed by the sk-03 event has partially filled up with ice.
    - For the same glacier, satellite imagery indicate an that an earlier detachment has likely occurred between 16 August and 01 September 2006 (insets in-

In the eastern part of the Shuraki Kapali catchment a KH-09 reconnaissance image from 03 August 1973, indicates a

- 460 rock-ice avalanche (sk-73; Fig. A2b), likely originating from the the glacier that produced the sk-17 detachment. From the runout distance of 3.3 km and the estimated fall height we calculated an angle of reach of around 14°. Large deposit pattern in an earlier KH image from 30 August 1961 (Fig. 8). A2a), an apparent widening of the valley until 1973, and the missing of the glaciers in the central and eastern catchment in a KH-4B image from 15 September 1971 indicate that the SK catchment has already been very active before the 1973 event occurred.
- 465 Imagery from before (a) and after (b) the small glacier detachment sha-19 in a side-valley of the Shaklysu river. A white arrow indicates the detachment scarp. (c, d) at the same place (white circle) an earlier detachment (sha-06) has very likely happened. The black box in the inset corresponds to the outline of the main images. (a, b) Google Maxar Technologies, CNES/Airbus. (c, d) Landsat-7 imagery courtesy of the U.S. Geological Survey.

#### 4.4 Avalanches in the Shikorchi (Shi) catchment

#### 470 4.3.1 Shikorchi (Shi) catchment

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In the catchment of the Shikorchi river, we identified a series of large mass flows which travelled over steep glaciers but we could not determine how much ice was involved, entrained during flow or involved in the release area. The runout did not show clear traces of ice, therefore we classified them as rock avalanches. This classification is supported by the relatively steep slopes  $(26-38^{\circ})$  and the low mobility (angles of reach  $17.6-19.6^{\circ}$ ) listed in Table 3.

- 475 In the *eastern part* of the catchment, likely a rock fall a rock avalanche (shi-01), occurred between 11 and 18 March 2001.
   occurred in March 2001, Fig. A6a. It originated at a relatively small area (16 × 10<sup>3</sup> m<sup>2</sup>) at 4000 m at the ridge of the catchmentand above a glacier with the ID G070941E39016N, run over another glacier with the ID G070934E39019N, ran across two glaciers (GLIMS IDs G070941E39016N and traveled in total G070934E39019N), and covered a total of 5.2 km over an elevation difference of 1680 m, Fig. ??a.
- At the same location two avalanches (shi-17, two rock avalanches of similar size (shi-17-1 and shi-17-2) occurred between 01, 08 and 02 and 03 June 2017, and between 19 and 21 June 2017, possibly triggered by rock fall. They run over the two (Fig. A6b and c). They flowed across the two same two glaciers, and the longest of these avalanche had a run out distance of had a runout distance of 3.9 and 4.4 km, respectively, over an elevation distance of , Fig. ??b. 1550 and 1600 m.
- 485 In the western part
  - In the western part of the catchment, we identified a mass flow which rock avalanche that occurred between 09 April 2009 and 11 May 2009, originated above the glacier with the ID G070926E39021N, traveling and travelled 5.3 km over 1680 m elevation, Fig. ??c. For none of these events we found any detached glacier and the origin of the avalanches rather indicates major rock fall events. This is supported by the relatively steep slope (26–38°) and high A6d.

## 490 4.3.2 Shaklysu catchment (Sha)

In a side-valley of the Shaklysu river a very small glacier with the GLIMS ID G070995E39014N is located.

- In July 2019, a long rock-ice avalanche originated from the upper reaches of the glacier at 3810 m. Exposed rocks at the former location of the glacier in Google Earth imagery indicate that the entire glacier has detached (Fig. 8). The resulting mass flow travelled 4.7 km over a vertical distance of 1320 m with an angle of reach (17.6–19.6 of 15.8°) as listed in Table 3. and almost reached the Shaklysu river. A maximum trim line height of 92 m indicates a high flow velocity. Satellite imagery indicate that the glacier was not existent in 2013 but built up mass until it detached in 2019.
- In August 2006, satellite imagery indicate a similar event (insets in Fig. 8).

## 4.4 Meteorology and seismic activity

#### Almost all detachments (eight out of nine) and 12 out of all 14 events-

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Almost all detected events (14 out of 17) occurred in years where the mean annual air temperature (MAAT) was above the long-term 46 years trend (Fig. 9). Only the sk-94 and sk-06 detachment event and the shi-09 rockfall event rock avalanche occurred in years with a MAAT below the trend. Except for rock avalanches, all events happened in between June and September which are the warmest months of the year. We interpret this in the sense that temperature has a very strong impact on the occurrence of glacier detachments. No correlation to precipitation was found.



**Figure 8.** Imagery from before (a) and after (b) the rock-ice avalanche sha-19 caused the disappearance of a small glacier in a side-valley of the Shaklysu river. A white arrow indicates the detachment scarp. (c, d) at the same place (white circle) an earlier rock-ice avalanche (sha-06) has happened. The black box in the inset corresponds to the outline of the main images. (a, b) ©Google, Maxar Technologies. (c, d) Landsat-7 imagery courtesy of the U.S. Geological Survey.

505 The magnitude of all earth quakes and distance of all earthquakes which occurred within a radius of 500 km of the SK catchment are shown in Fig. 9 as green bars. Earth quakes which 10 as gray dots. The solid lines indicates the threshold for triggering disrupted landslides (Jibson, 2013). As we do not know the sensitivity of glacier detachments and rock-ice avalanches to earthquakes, we shifted the threshold disrupted landslides by one and two earthquake magnitudes (dashed and dotted line). Earthquakes that occurred between the pre-event and post-event satellite image according to (Table 4are) and that

510 are close enough and strong enough to be at least below the dotted line (magnitude for disrupted landslides - 2) are shown as black bullets; black dots indicate earth quakes which occurred up to before the pre-event image.

For earthquakes with a magnitude above 5.0 we observed no detachment or major rockfall event. On 06 July 2006 an mag 5.8 earth quake occurred southeast of the SK eatchment area but before the sk-06 event. The largest earth quake (mag 4.9, 29 April 2009) which occurred within the possible time-period April–May 2009 of the rock avalanche shi-09 happened east of the

515 catchment in a year with below-trend temperatures. The second largest earth quake (mag 4.5, 03 August 2019) which occurred



**Figure 9.** Mean annual air temperature (eyanMAAT) at of ERA-5 Land reanalysis data obtained for 3470 m a.s.l. (red). The MAAT of the Lyairun station at 2008 m a.s.l. (Williams and Konovalov, 2008) (magenta) was shifted by -7.6°C to match the ERA-5 Land reanalysis ERA data(Copernicus Climate Change Service (C3S), 2019) obtained for (. The red )dashed line indicates the temperature trend. Detachments, ice and other events rock-ice avalanches are indicated by  $\star$  and symbols, rock avalanches by + symbolsand. Events are vertically distributed stacked when more than one event occurred in the same year. Seismie events (green) with mag >3.5 are frequent within a radius. The magnitude of of the Petra Pervogo range: black bullets indicates earth quakes which seismic events that occurred between the pre-and post-event post event image (Table 4) and black dots that are earth quakes which occurred up to 14 days before within the pre-event imagerange indicated by the dotted line in Fig.10 are indicated by black dots. Figure contains modified Copernicus Climate Change Service Information (2020); Earth quake-earthquake data from USGS via IRIS Data Services.

within the time period of the dp-19 detachment happened west of the dp-19 detachment. Other earth quakes were below mag 4.5. Although several earth quakes happened in temporal proximity of the detachment or rock fall events, there were a large number of earth quakes which are not related to any event, especially the stronger ones. Therefore. We found no mass flow events that could have been triggered by earthquakes below the dashed line (magnitude for disrupted landslides - 1). Because stronger earth quakes did not trigger any mass flows, we conclude that is is very unlikely that the detachment events were triggered by seismic activityrock/ice avalanches and detachments are not especially sensitive to earth quakes.

#### 4.5 Comparison with surging glaciers in the Pamir

In total, we identified 237 glaciers in the entire Pamir mountains which were either in a surge- or in where DEM differences (W3D - SRTM) showed a height change indicating either an active surge or a quiescence phase. Of these 188 showed both an



Figure 10. Proximity and magnitude of earth quakes which occurred within a 500 km radius around the analyzed catchment areas (gray dots). The solid lines indicates the threshold for triggering disrupted landslides (Jibson, 2013); the dashed and dotted lines represent the same line but shifted by one and two magnitudes, respectively. Black dots indicate earth quakes that occurred between an pre- and post event image of the analyzed events and that are closer or stronger to be located below the dotted threshold.

elevation increase at the terminus and a decrease further up, 32 glaciers showed only an elevation increase at the terminus and 525 17 seemed to be in a quiescent phase with strong melt at the tongue but mass gain in a possible reservoir area.

In the Petra Pervogo range we found four surge-type glaciers, listed from East to West: at 38.925° N, 70.524° E a glacier surged between 2001 and 2006; at 38.937° N, 70.695° E a glacier surged between 1993-1996; at 38.994°, 70.725° a glacier surged started in June 1995 and advanced by remarkable 2.3 km within 7 months. The glacier retreated and surged again between June 2015 and July 2016 where it advanced by 5 km. The lower glacier entering the SK catchment from the left (Fig. 7) surged in autumn 1993 and also in 2010/2011, each time entering the valley of the SK catchment.

The comparison in Fig. 11 of the slope and length of all surging glaciers with the detached glaciers of the the largest events, dp-19, sk-17, and sk-03 +06and sk-04, and in addition with the Aru- and Kolka-Karmadon detachments, shows that glacier detachments occur predominantly for short but steep glaciers, at least when compared to glaciers which showed a surge-like instability in the past.

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#### 4.6 **Retroactive avalanche detection using NDVI**

The largest avalanches in this study, sk16-bsk16b, sk-17, sk-19, and dp-19, were identified in satellite imagery by destruction of vegetation in the associated valleys. Unfortunately, most other avalanches travelled in already eroded valleys, therefore it was difficult to detect them by means of vegetation change only and the panchromatic channels of L7 and L8 provided more



Figure 11. Horizontal length over slope of the surging part of glacier in the Pamir Mountains and surface slope of the detached parts of glacier detachments.

- 540 spatial details than the NDVI. Nevertheless, an valleys. The analysis of time-series of the NDVI evolution in the DP- and SK-catchment, Fig. 12, shows that it within two years between events the vegetation hardly recovers vegetation did not recover within the two years of the events. In the run out runout zone of the Kolka-Karmadon detachment, where a suitable long satellite time series exist and where no repeated avalanches occurred, vegetation recovery to pre-detachment NDVI values takes took around 10 years (Fig. A1). Because of similar climatic conditions The vegetation covered runout zones of the SK/DP catchment
- 545 at roughly 2500 m and the runout of the Kolka-Karmadon detachment at 1800 m (Haeberli et al., 2004) show a similar climate: for SK/DP we obtain a MAAT of +4.5 °C which is comparable to the a MAAT of +4.0 °C below the Kolka-detachment. The similar climatic conditions indicate that vegetation recovery times are comparable. Therefore, we conclude that the chance of missing long run outs runouts of mass flows that reach vegetated areas is very low when imagery every few years is available. Unfortunately, most other avalanches travelled in already eroded valleys, therefore it was difficult to detect them by means of
- 550 vegetation change only. We observed that the white color of ice avalanches quickly disappeared within a few days. Therefore, it is likely that smaller events have been missed, especially in years with frequent cloud cover. Therefore we are confident that we did not miss any major events .

#### 5 Discussion

The numerous recent discoveries of glacier detachments around the world (Kääb et al., 2018; Gilbert et al., 2018; Falaschi et al.,
 2019; Paul, 2019; Jacquemart et al., 2020) have raised important questions about the conditions and triggers leading a glacier to detachto these events. Our analysis of the 46-year of satellite record over the Petra Pervogo range has revealed a cluster



**Figure 12.** (a) NDVI before the sk-16b detachment. The white bar indicate the end of the <u>run out runout</u> of the sk-17 and sk-19 event, the sk-16b mud flow traveled further, (b) NDVI after the sk-17 detachment, (c, d) NDVI before and after the dp-19 detachment. The time series of the mean NDVI obtained from L8 and S2 over the eroded area in the black box show that vegetation does hardly recover within two years. Copernicus Sentinel data (2020) and Landsat-8 image courtesy of the U.S. Geological Survey.

of such events in a small geographical area that provides additional understanding of these catastrophic events, in particular with regard to the link between surging glaciers and glacier detachments, and the influence of climate change temperature and seismic activity.

#### 560 5.1 Detachment detection

Analyzing the entire satellite record is frequently the only way to assess the occurrence of past large mass flow events in a given geographical area (Coe et al., 2018; Bessette-Kirton and Coe, 2020). This approach is not fool proofnot a fool proof approach, since clouds and shadows may have obstructed can hamper the detection of certain events, but we always compared multiple consecutive images and in addition as well as images acquired in the same month of consecutive years, therefore we are

- <sup>565</sup> reasonably certain that we did not miss any large events, especially in more recent years. While the traces left by smaller events easily disappear against the background of loose sediment and hillslopes free of vegetation, large events that reach vegetated areas leave distinct traces that can be detected for several years. Our analysis of vegetation recovery at Kolka-Karmadon (approximately 10 years), and the fact that we discovered sk-17 and dp-19 in this fashion, demonstrate how the NDVI and the vegetation sensitive NIR channel are good means to detect long-runout events in remote sensing imagery, even years after
- 570 they happened. Closer to the source, where vegetation in strongly eroded valleys is missingthere is typically no vegetation, the moisture sensitive channels SWIR1 and SWIR2 of Landsat -7 and -8 allow for the detection of sediment-covered ice, at least several until at least a few weeks after detachment; in addition, they allow for separation of snow and clouds. Lastly, the low resolution of 80 and 30 m of Landsat 1–5, which lack a higher resolution panchromatic channel and especially the lower number of available images, could impede the detection of some early events. To complement the drawbacks of all-optical
- 575 methods (especially in areas with poor color contrast), and in particular for the detection of more recent events, detecting optically visible changes differencing high resolution DEMs, acquired within a period of months to a few years, is undoubtedly the most reliable way to detect drastic changes in glaciated catchments; however, such DEM data is currently not acquired operationally and is only sparsely available in time and coverage. We found that weather-insensitive radar imagery is helpful to detect abrupt changes, but the bright backscatter signatures of avalanches disappears quickly-ice avalanches disappears within
- 580 a few days due to melt. Due to increasing availability of imagery (Fig. 2), we are relatively certain that our dataset is biased towards more frequent events, hence, no conclusion can be drawn from the relative frequency of detected events. Repeated single-pass radar DEMs provided by TanDEM-X are an excellent mean to detect drastic topographic changes, however such data is not systematically available at annual resolution.

In contrast to the detection of past events, detection of glaciers that may be prone to detach in the future is a much more difficult task. On sk-17 and dp-19, increased crevassing could be only seen in high resolution images few of a few weeks prior to the detachment. This makes it extremely difficult to identify possible instabilities sufficiently early, especially when a glacier is not inspected on a regular basis. SimilarSimilarly, the Aru glaciers also showed increased crevassing just a few weeks before their detachments (Kääb et al., 2018). Indeed, even the supposedly tell-tale crevasses don't always reliably predict a detachment. For example, a small glacier near the Gulyia-Ice cap in the western Kunlun Shan has been showing detachment-

590 like crevasses since early 2018 (Leinss et al., 2019), but has remained stable so far, likely due to the stabilizing effect of its

Table 5. Characteristics of the glaciers listed by catchment where we identified detachments and rock-ice avalanches. For glacier identification, only the most recent detachments are used as column title. For a full list see Table 3.

Measure	sk03+06sk-center	sk-17-sk-east	sk-16b-sk-west	<del>dp-19_dp</del>	<del>sha-19sha</del>
Glacier length (m)	1080	1590	1100	1350	400-700
Glacier width (m)	250	270	350	300	130
Aspect	Ν	NW	NE	NE	Е
Lowest point (m)	3410	3310	3550	2862	3450
Highest point (m)	3820	3900	4100	3400	3800
Mean slope (°)	22.3	21.8	30.0	23.5	24.9

very broad tongue. Another option for an early identification of possible detachments would be through automated Automated near real-time mapping of velocities velocity monitoring using very high resolution sensors could be another option for early glacier hazard identification. However, based on our experience, the detached glaciers in the Petra Pervogo range are too small for current optical or radar sensors like S1, S2 or Landsat to provide reliable velocity estimates. Increased data bandwidth and imaging capabilities of future sensors and high-repeat rate DEM differencing satellites could provide the required data for 595 early detection of possible detachments. In the specific catchments of this study, where we large mass flows occur frequently, in situ observation observations by radar or cameras could very likely act as an relatively cheap warning systems to inform local population in time.

#### 5.2 **Detachment characteristics and triggers**

- Fundamentally, the question of which events to classify as glacier detachments failures of low-angle valley glaciers that 600 involve substantial amounts of the glacier - is a tricky one when the observations are purely based on remotely sensed imagery. In our study region, the task is further complicated by wide spread debris cover, which makes it hard to delineate glaciers. While the boundaries of the glacier detachment category are certainly fuzzy, we have classified nine of the fourteen four of the 16 detected events listed in Table 3 as eertain or likely glacier detachments. We based out classification on satellite imagery and elassified glaciers located in a valley or at least in a topographic depression as detachment when major parts of the ice volume 605
- detached. The posterior analysis of the detachment events shows that all share the characteristic low to medium surface slope of the detached area  $(\frac{15-25}{15-20^{\circ}})$  and that all occurred in a location where the GLIMS database (Raup et al., 2007) indicated the presence of a glacier. When using only satellite imagery for classification, the transition from detachment to rock-ice avalanche seems to be continuous as the amount of detached rock is hard to quantify and deposits can contain entrained sediments or
- 610 sediments from the bedrock. Some of the events classified by us as rock-ice avalanche might well be glacier detachments of glaciers with a relatively steep slope  $(20-25^{\circ})$ . Remarkably, all events presented in this study happened within a roughly 30 km radius and the glaciers in the catchment areas present very similar characteristics regarding elevation and aspect (Table 5), with the SK catchment, for which the GLIMS data base lists five separate glaciers, appearing to provide particularly favorable conditions for detachments and rock-ice avalanches.

- 615 Henceforth, we focus our discussion on these events, in particular on the largest detachments sk-17 and dp-19. In comparing these two events with other detachments described in literature (in particular Aru, Kolka-Karmadon and Flat Creek), we find similarities in slope, lithology and the time of year of the events. Both images and the described lithology (sedimentary) suggest that the easily erodible bedrock and soft sediments are abundant in our study area. Similar to Kolka glacier, dp-19 was below a steep headwall and detached at the Bergschrund, so that the resulting mass movement involved basically the entire glacier.
- As has been reported for other glacier detachments (Kääb et al., 2018; Gilbert et al., 2018; Jacquemart and Loso, 2019), there is a remarkable proximity, or in some cases overlap, between detaching and surging glaciers. Like others, we identified hundreds of surging glaciers throughout the Pamir, and the spatial distribution of the surging glaciers identified in our study is similar to Goerlich et al. (2020, Fig. 6). By comparison of the spatial distribution of surging glaciers with the rock types according to the geological map by Ibrohim et al. (around 1974) we found that surging glaciers occur predominantly in regions with soft and fine-grained rock-types. It is noteworthy, though the importance and effect not yet well understood, that the glaciers that
- later detached (sk-17 and dp-19 in out our study, but also the Aru and Kolka glaciers) exhibited a slightly steeper slope and were relatively short compared to their non-detaching surging neighbors (Fig. 11). Both sk-17 and dp-19 have surged in the past, but neither were in the midst of a surge immediately before their detachment, nor did they show any surge-like behavior. They did, however, show a significant acceleration in the weeks prior to the detachment. Therefore, we do not believe that
- 630 sk-17 or dp-19 were the consequence of a "runaway surge", but that both glacier surging and glacier detachments are favoured by a soft sedimentary bedrock. We rather conclude that the detachments were triggered by external drivers: because velocities increased during or after snowmelt, we suspect that increased liquid water input played a crucial role in lubricating the glacier base or saturating the underlying glacier bed (Gilbert et al., 2018). This idea is supported by the fact that all detachments in this study happened in summer (July–Septemberend June–September), when more liquid water is available and making it's
- 635 influence on the glacier dynamics is greater. We did not find any obvious indication that earthquakes could have triggered the detachments or rock-ice avalanches. Instead, we have observed that 12 out of 14 14 out of 17 mass movements, including the eight out of nine detachments, 11 out of 13 detachments, ice or rock-ice avalanches occurred in years when the mean annual air temperature was above the long-term trend . linear trend of the past 46 years. Even though we think that our dataset is biased towards detection of more recent events, the comparison to the linear trend provides an indicator for the sensitivity to
- 640 temperature, while the comparison to the average temperature should results in a observational bias that we tried to avoid.

The fact that relatively short and steep glaciers (compared to their surging neighbours) show detachments could be related to the reason that short glaciers are more likely to have a more homogeneous slope compared to long glacier. When enhanced melt water lubricates the homogeneous base of a short glacier it is **much**-more likely to detach compared to a long glacier where lubrication might be cause a more local effect and could possibly init a surge-cycle when a sufficiently high mass imbalance is present.

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All of the investigate investigated events were very mobile, though at first glace, their mobility, characterized by an angle of reach of around  $\alpha = 10 - 15^{\circ}$ , was lower than that of the events at Aru and Kolka ( $\alpha = 5 - 8^{\circ}$ ) (Huggel et al., 2005; Kääb et al., 2018). The lower mobility can be partly explained by the smaller volume involved (Petra-Pervogo:  $3 - -9 \times 10^{6} \text{ m}^{3}$ , the others  $70-130\times10^{6} \text{ m}^{3}$ ). However, if we compute the ratio V/L between detachment volume and runout distance, the ratio

is one to two orders of magnitude smaller compared to the Kolka and Aru detachments, indicating an extremely high mobility. 650 This could be a consequence of the path geometry, which channelized the avalanches over a very long distance in a small area. The valleys of easily erodible sediments provided few obstacles and thus small energy loss. In addition, we think the exceptionally long run out run out of 19.1 km of the debris flow event sk-16b, which angle of reach of  $\alpha = 7.7^{\circ}$  is comparable to the other large events, is caused by entrainment of the ice-water-sediment mixture deposited in the catchment by the sk-16a 655 event five weeks before. A video of the event shows that the debris flow is almost as liquid as water (Radio Ozodi, 2016).

#### 6 Conclusions

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In this study we build built an inventory of glacier detachments and ice or rock-ice avalanches which occurred in the western Petra Pervogo range in Tajikistan. Compared to a handful of other large glacier detachments around the entire world we found a cluster of at least nine, four relatively small detachments and seven rock-ice avalanches within a radius of 30 km. The fact that multiple detachments occurred under very similar conditions (elevation, aspect, size, meteorological conditions) allows for studying external driving factors which can trigger the detachment of a valley glacier. We found that detachments occur in years with summer and in years with annual mean air temperature above the long term 46-year trend, indicating that with rising temperatures more detachments can be expected and that climate change has an direct impact on the occurrence

of glacier detachments high temperatures are an important factor favouring glacier detachments and rock-ice avalanches. The

- 665 comparison to the temperature trend instead to the mean temperature reduces the observational bias resulting from the increased availability and resolution of satellite imagery. Despite being a seismic active region, no immediate effect of earth quakes could be observed we found that earthquakes are very unlikely to be the cause of mass wasting events in our study site. Similar to other detachments, the glaciers in our study rest on a bedrock of soft sediments. We found For a rock-ice avalanche end of August 2016, we think that the entrainment of sediment-ice debris mixture from a previous ice avalanche detachment of
- 670 relatively small volume five weeks before eaused an-was the reason of the resulting, extraordinary long mud flow of 19.1 km. We also observed a spatial correlation between the occurrence of surging glaciers in the Pamir mountains and soft, fine-grained sediments. However, we did not observe that the studied glacier detachments were a consequence of surging but we think that soft sediments are a prerequisite for detachments and at least a favouring factor for hydrologically controlled glacier surging. This is supported by our observation that detachments occurred predominantly in summer after snow melt and in years with
- 675 above-trend temperatures. From the fact that the studied detached glaciers are shorter and steeper compared to surging glaciers in the same region we hypothesize that melt water penetrating to the glacier base can lubricate major parts of the relatively small bedrock of soft sediments which then can lead to detachment of the entire glacier, especially if the glacier is relatively steep and the destabilized area is not supported by a stabilizing tongue of smaller-lower slope. In contrast, for longer glaciers it is unlikely that the entire glacier loses friction at the bedrock and it might instead be more likely that the glacier shows a 680 temporary surge-like advance.



**Figure A1.** L7 false color images (Band 7,8,3 = SWIR, pan, red) from 07 July 2004 and 01 August 2013 show that vegetation on the Kolka-Karmadon rock-ice avalanche has recovered within about 10 years. The stripes are due to the failure of the scan line correlator of L7 in 2003. Landsat-7 image courtesy of the U.S. Geological Survey.

*Code and data availability.* S2, L1–8, ASTER, and Sentinel-1 data are available in the Google Earth Engine data catalogue and were processed with the Google Earth Engine (Gorelick et al., 2017) with Java scripts available on request from the authors. Some Copernicus S-2 data and USGS L8 data were also processed by ESA and downloaded form the Sentinel hub with the EO Browser: https://www.sentinel-hub. com/explore/eobrowser/. Declassified Keyhole imagery is available from the NASA USGS Earth explorer https://earthexplorer.usgs.gov/. TanDEM-X data is available from DLR https://tandemx-science.dlr.de/ and was provided by the proposal leinss\_ XTI\_ GLAC6600. Digital-Globe data were provided by the Commercial Archive Data for NASA investigators (cad4nasa.gsfc.nasa.gov) under the National Geospatial-Intelligence Agency's NextView license agreement. The SRTM DEM is available from the USGS; The W3D is commercially available at 5 m resolution but we used the freely available 30 m resolution provided by JAXA. The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access the seismic products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience (SAGE) Award of the National Science Foundation under Cooperative Support Agreement EAR-1851048.

#### Appendix A: Additional imagery of detachments and avalanches

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Figure A2. Keyhole images from 30 August 1961 and 03 August 1973 KH-9 image of the SK-SK-73 rock-ice avalanche in the eastern Shuraki-Kapali catchment area. In (a03 August 1973)the tongue of a pre-1961 surge from the western tributary is indicates the debris front. In (b) the debris front has advanced, the valley bottom appears widened, is filled with more debris and a new ice-avalanche covers the valley bottom and parts-Courtesy of the pre-1961 surge front. The visible avalanche looks very similar to the sk-06 avalanche in Fig. ??b. (a) Keyhole-3 image (DS009023023DV206\_206\_d) and (b) Keyhole-7 image (DZB1206-500080L018001), courtesy of the U.S. Geological survey.



**Figure A3.** (a) The KH-3 image from 30 August 1961 shows strong erosion in the entire Shuraki-Kapali catchment. (b,c): mass flow events in the western sub-catchment. (b) L5 image of the sk-94 rock-ice avalanche (22 July 1994). (c) ASTER image of the sk-04 detachment (18 September 2004) followed by an ice avalanche (inset: 04 October 2004). Imagery with courtesy of the U.S. Geological survey.



**Figure A4.** Mass flow events in the western Shuraki-Kapali sub-catchment. (a) L5 image of the sk-10 rock-ice avalanche (04 September 2010); (b) L8 image of the sk-16b rock-ice avalanche (20 September 2016). The trim line of the event is indicated by dots. One arrow indicates where the rock/ice mass detached; the other arrow shows where trees were removed by the resulting mass flow. The inset shows the alluvial fan 19 km downstream where a mud flow reached the Surkhob river. (c) S2 image of the sk-19 ice/rock avalanche (01 July 2019). ASTER and L8 imagery courtesy of the U.S. Geological Survey; Copernicus Sentinel Data (2020).



Figure A5. Mass flow events in the central Shuraki-Kapali sub-catchment (a) Image from L7 image one year after the sk-03 detachment (10 August 2004showing the missing glacier in the white box (); The lower inset from shows the pre-event image (24 August 2003). The end of ; the ice avalanche sk-03 ice-rich runout is shown in the upper inset (ASTER, 25 September 2003), (b,e) ASTER image of the ice avalanches sk-06 that broke off above the sk-03 detachment (image from 08 September 2006)and avalanche sk-16a. (c) S2 image from of the detachment sk-16a (26 July 2016) that originated from the same location as sk-03. Landsat-7 and ASTER image courtesy of the U.S. Geological Survey. Copernicus Sentinel Data (2020).

(a) image from 18 September 2004 (inset: 04 October 2004) of the sk-04 detachment, (b) The trim line of the sk-16b detachment is indicated by dots in the L8 image from 20 September 2016. One arrow indicates the rupture line of the detachment and the other arrow (at the top of the image) trees removed by the resulting debris flow. The inset shows the alluvial fan downstream where the mud flow reached the Surkhob river. (c) images from 01 July 2019 of the sk-19 ice/rock avalanche. ASTER and Landsat-8 imagery courtesy of the U.S. Geological Survey; Copernicus Sentinel Data (2020).



**Figure A6.** (a,b)<del>image from :</del> rock avalanches in the eastern part of the Shikorchi catchment. (a) L7 of the shi-01 rock avalanche (18 March 2001of the shi-03 event), (b) S2 image from 21 June 2017 of the (second) shi-17 rock /iee avalanche (21 June 2017), (c) image from 23 July 2009 rock avalanche shi-09 in the western part of the shi-09 avalanche. Shikorchi catchment (image composed from two L7 images from 11 and 27 May 2009. Landsat-7 image courtesy of the U.S. Geological Survey; Copernicus Sentinel data (2020).

*Author contributions.* SL, EB, MJ jointly wrote the manuscript, SL processed the TanDEM-X data and wrote the Google Earth scripts, SL, EB analyzed the data, MJ computed the World View DEMs differences and calculated uncertainty estimates, MD provided relevant local information, initiated the seismic study, and indicated two of the detachments, SL coordinated the study.

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#### 700 References

- Bessette-Kirton, E. K. and Coe, J. A.: A 36-Year Record of Rock Avalanches in the Saint Elias Mountains of Alaska, With Implications for Future Hazards, Frontiers in Earth Science, 8, 293, https://doi.org/10.3389/feart.2020.00293, 2020.
- Clarke, G., Collins, S., and Thompson, D.: Flow, thermal structure, and subglacial conditions of a surge-type glacier, Canadian Journal of Earth Sciences, 21, 232–240, https://doi.org/10.1139/e84-024, 2011.
- Coe, J. A., Bessette-Kirton, E. K., and Geertsema, M.: Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery, Landslides, 15, 393–407, https://doi.org/10.1007/s10346-017-0879-7, 2018.
   Copernicus Climate Change Service (C3S): C3S ERA5-Land reanalysis, https://doi.org/10.24381/cds.68d2bb30, date of access: 2020-08-06, 2019.

Cuffey, K. M. and Paterson, W. S. B.: The physics of glaciers, Academic Press, 2010.

710 Davies, T. R. H.: Spreading of rock avalanche debris by mechanical fluidization, Rock mechanics, 15, 9–24, https://doi.org/10.1007/BF01239474, 1982.

Dokukin, M.: https://twitter.com/inrushmd/status/1059061814691012608, 2018.

Dokukin, M. D., Bekkiev, M. Y., Kalov, R. H., Savernuk, E. A., and Chernomorets, S. S.: Signs of catastrophic glacier detachments (Analysis of multitemporal space information) (In Russian), in: Dangerous natural and technogenic processes in mountain regions: models, systems

and technologies, edited by Nikolaev, A. and Zaalishvili, V., pp. 522–528, https://istina.msu.ru/publications/article/266605247/, 2019.
 Drobyshev, V.: Glacial catastrophe of 20 September 2002 in North Osetia, Russian Journal of Earth Sciences, 8, 1–25, https://doi.org/10.2205/2006ES000207, 2006.

ESA, E. S. A.: Sentinel-2 User Handbook, 2015.

Evans, S. G. and Delaney, K. B.: Chapter 16 - Catastrophic Mass Flows in the Mountain Glacial Environment, in: Snow and Ice-Related

- 720 Hazards, Risks and Disasters, edited by Shroder, J. F., Haeberli, W., and Whiteman, C., pp. 563 606, Academic Press, Boston, https://doi.org/10.1016/B978-0-12-394849-6.00016-0, 2015.
  - Evans, S. G., Tutubalina, O. V., Drobyshev, V. N., Chernomorets, S. S., McDougall, S., Petrakov, D. A., and Hungr, O.: Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002, Geomorphology, 105, 314–321, https://doi.org/10.1016/j.geomorph.2008.10.008, 2009.
- 725 Faillettaz, J., Sornette, D., and Funk, M.: Numerical modeling of a gravity-driven instability of a cold hanging glacier: reanalysis of the 1895 break-off of Altelsgletscher, Switzerland, Journal of Glaciology, 57, 817–831, https://doi.org/10.3189/002214311798043852, 2011.
  - Falaschi, D., Kääb, A., Paul, F., Tadono, T., Rivera, J., and Lenzano, L.: Brief communication: Collapse of 4 Mm 3 of ice from a cirque glacier in the Central Andes of Argentina, The Cryosphere, 13, 997–1004, https://doi.org/10.5194/tc-13-997-2019, 2019.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer,

- 730 S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., and Alsdorf, D.: The Shuttle Radar Topography Mission, Reviews of Geophysics, 45, https://doi.org/10.1029/2005RG000183, 2007.
  - Finaev, A., Shiyin, L., Weijia, B., and Li, J.: Climate Change and Water Potential of the Pamir Mountains, Geography, Environment, Sustainability, 9(3), 88–105, https://doi.org/10.15356/2071-9388\_03v09\_2016\_06, 2016.

Gilbert, A., Leinss, S., Kargel, J., Kääb, A., Gascoin, S., Leonard, G., Berthier, E., Karki, A., and Yao, T.: Mechanisms leading to the 2016
giant twin glacier collapses, Aru Range, Tibet, The Cryosphere, 12, 2883–2900, https://doi.org/10.5194/tc-12-2883-2018, 2018.

- Goerlich, F., Bolch, T., and Paul, F.: More dynamic than expected: an updated survey of surging glaciers in the Pamir, Earth System Science Data, 12, 3161–3176, https://doi.org/10.5194/essd-12-3161-2020, 2020.
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R.: Google Earth Engine: Planetary-scale geospatial analysis for everyone, Remote Sensing of Environment, https://doi.org/10.1016/j.rse.2017.06.031, 2017.
- 740 Haeberli, W., Huggel, C., Kääb, A., Zgraggen-Oswald, S., Polkvoj, A., Galushkin, I., Zotikov, I., and Osokin, N.: The Kolka-Karmadon rock/ice slide of 20 September 2002: an extraordinary event of historical dimensions in North Ossetia, Russian Caucasus, Journal of Glaciology, 50, 533–546, https://doi.org/10.3189/172756504781829710, 2004.
  - Harrison, W. D. and Post, A. S.: How much do we really know about glacier surging?, Annals of Glaciology, 36, 1–6, https://doi.org/10.3189/172756403781816185, 2003.
- 745 Huggel, C., Zgraggen-Oswald, S., Haeberli, W., Kääb, A., Polkvoj, A., Galushkin, I., and Evans, S. G.: The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery, Natural Hazards and Earth System Sciences, 5, 173–187, https://doi.org/10.5194/nhess-5-173-2005, 2005.
  - Ibrohim, A., Verhov, V. I., Dyakov, Y. A., Vlasov, N., Bakhtdavlatov, R. D., Rahmonov, I. U., Bobomurodov, O. M., Nurov, T., and Ormonov, O.: Geological and Mineral Resource Map of Tajikistan, http://www.geoportal-tj.org/index.php/geology/deposits, last accessed: 2020-08-
- 750 03, around 1974.
  - Jacquemart, M. and Loso, M.: Catastrophic Glacier Collapse and Debris Flow at Flat Creek, Wrangell-St. Elias National Park and Preserve, Alaska Park Science, 1, 16–25, https://www.nps.gov/articles/aps-18-1-3.htm, 2019.
  - Jacquemart, M., Loso, M., Leopold, M., Welty, E., Berthier, E., Hansen, J. S., Sykes, J., and Tiampo, K.: What drives large-scale glacier detachments? Insights from Flat Creek glacier, St. Elias Mountains, Alaska, Geology, 48, 703–707, https://doi.org/10.1130/G47211.1, 2020.
- 755
  - Jibson, R.: 7.23 Mass-Movement Causes: Earthquakes, in: Treatise on Geomorphology, edited by Shroder, J. F., pp. 223–229, Academic Press, San Diego, https://doi.org/10.1016/B978-0-12-374739-6.00169-X, 2013.
  - Kääb, A., Bolch, T., Casey, K., Heid, T., Kargel, J. S., Leonard, G. J., Paul, F., and Raup, B. H.: Glacier Mapping and Monitoring Using Multispectral Data, pp. 75–112, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/978-3-540-79818-7\_4, 2014.
- 760 Kääb, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoin, S., Evans, S. G., Bartelt, P., Berthier, E., Brun, F., Chao, W.-A., Farinotti, D., Gimbert, F., Guo, W., Huggel, C., Kargel, J. S., Leonard, G., Tian, L., Treichler, D., and Yao, T.: Massive Collapse of Two Glaciers in Western Tibet in 2016 after Surge-like Instability, Nat. Geosci., 11, 114–120, https://doi.org/doi:10.1038/s41561-017-0039-7, 2018.
  - Kääb, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E., and Kargel, J.: Sudden large-volume detachments of low-angle mountain glaciers more fre-
- 765 quent than thought, The Cryosphere Discussions, 2020, 1–52, https://doi.org/10.5194/tc-2020-243, https://tc.copernicus.org/preprints/ tc-2020-243/, 2020.
  - Kamb, B., Raymond, C., Harrison, W., Engelhardt, H., Echelmeyer, K., Humphrey, N., Brugman, M., and Pfeffer, W.: Glacier Surge Mechanism: 1982-1983 Surge of Variegated Glacier, Alaska, Science (New York, N.Y.), 227, 469–79, https://doi.org/10.1126/science.227.4686.469, 1985.
- 770 Krieger, G., Fiedler, H., Zink, M., Hajnsek, I., Younis, M., Huber, S., Bachmann, M., Hueso Gonzalez, J., Werner, M., and Moreira, A.: TanDEM-X: A satellite formation for high-resolution SAR interferometry, IEEE Trans. Geosci. Remote Sens., 45, 3317–3341, https://doi.org/10.1109/TGRS.2007.900693, 2007.
  - Kääb, A.: Private communication, 2020.

Leinss, S. and Bernhard, P.: TanDEM-X: Deriving Height and Velocity Dynamics of Great Aletsch Glacier, IEEE Journal of Selected Topics

of Remote Sensing, in review, 2021.

- Leinss, S., Willimann, C., and Hajnsek, I.: Glacier Detachment Hazard Analysis in the West Kunlun Shan Mountains, in: IGARSS 2019 2019 IEEE International Geoscience and Remote Sensing Symposium, pp. 4565–4568, 2019.
- Lied, K. and Toppe, R.: Calculation of Maximum Snow-Avalanche Run-Out Distance by use of Digital Terrain Models, Annals of Glaciology, 13, 164–169, https://doi.org/10.3189/S0260305500007825, 1989.
- 780 McClung, D. M. and Gauer, P.: Maximum frontal speeds, alpha angles and deposit volumes of flowing snow avalanches, Cold Regions Science and Technology, 153, 78 – 85, https://doi.org/10.1016/j.coldregions.2018.04.009, 2018.
  - Miles, E. S., Watson, C. S., Brun, F., Berthier, E., Esteves, M., Quincey, D. J., Miles, K. E., Hubbard, B., and Wagnon, P.: Ablative and geomorphic effects of a supraglacial lake drainage and outburst event, Nepal Himalaya, The Cryosphere, 12, 3891 – 3905, https://doi.org/10.5194/tc-2018-152, 2018.
- 785 Moore, P. L.: Deformation of debris-ice mixtures, Reviews of Geophysics, 52, 435–467, https://doi.org/10.1002/2014RG000453, 2014. Neigh, C., Masek, J., and Nickeson, J.: High-Resolution Satellite Data Open for Government Research, EOS, Transactions, American Geophysical Union, 94, 121–123, https://doi.org/10.1002/2013EO130002, 2013.
  - Noh, M. J. and Howat, I. M.: The Surface Extraction from TIN based Search-space Minimization (SETSM) algorithm, ISPRS Journal of Photogrammetry and Remote Sensing, 129, 55–76, https://doi.org/10.1016/j.isprsjprs.2017.04.019, 2017.
- 790 Nuth, C. and Kääb, A.: Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change, The Cryosphere, 5, 271–290, https://doi.org/10.5194/tc-5-271-2011, 2011.
- Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., Khomutov, A., Kääb, A., Leibman, M. O., Lewkowicz, A. G., Panda, S. K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T., Yamkhin, J., and Zou, D.: Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2
   scale, Earth-Science Reviews, 193, 299 316, https://doi.org/10.1016/j.earscirev.2019.04.023, 2019.
  - Paul, F.: Repeat Glacier Collapses and Surges in the Amney Machen Mountain Range, Tibet, Possibly Triggered by a Developing Rock-Slope Instability, Remote Sensing, 11, https://doi.org/10.3390/rs11060708, 2019.
    - Petrakov, D., Chernomorets, S., Evans, S., and Tutubalina, O.: Catastrophic glacial multi-phase mass movements: A special type of glacial hazard, Advances in Geosciences, 14, https://doi.org/10.5194/adgeo-14-211-2008, 2008.
- 800 Prochaska, A. B., Santi, P. M., Higgins, J. D., and Cannon, S. H.: Debris-flow runout predictions based on the average channel slope (ACS), Engineering Geology, 98, 29 – 40, https://doi.org/10.1016/j.enggeo.2008.01.011, 2008.
  - Quincey, D., Braun, M., Glasser, N. F., Bishop, M., Hewitt, K., and Luckman, A.: Karakoram glacier surge dynamics, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL049004, 2011.
  - Radio Ozodi: Радиои Озоди: Отколовшаяся часть ледника разрушила несколько домов в Таджикабаде (ВИДЕО), https:
- 805 //rus.ozodi.org/a/27952776.html, date of access: 2020-08-26, 2016.
  - Raup, B., Racoviteanu, A., Khalsa, S. J. S., Helm, C., Armstrong, R., and Arnaud, Y.: The GLIMS geospatial glacier database: a new tool for studying glacier change, Global and Planetary Change, 56, 101–110, 10.1016/j.gloplacha.2006.07.018, 2007.
  - Rignot, E., Echelmeyer, K., and Krabill, W.: Penetration depth of interferometric synthetic-aperture radar signals in snow and ice, Geophysical Research Letters, 28, 3501–3504, https://doi.org/10.1029/2000GL012484, 2001.
- 810 Scheidegger, A. E.: On the prediction of the reach and velocity of catastrophic landslides, Rock mechanics, 5, 231–236, https://doi.org/10.1007/BF01301796, 1973.

Schneider, D., Huggel, C., Haeberli, W., and Kaitna, R.: Unraveling driving factors for large rock-ice avalanche mobility, Earth Surface Processes and Landforms, 36, 1948-1966, https://doi.org/10.1002/esp.2218, 2011.

Schweizer, J., Bruce Jamieson, J., and Schneebeli, M.: Snow avalanche formation, Reviews of Geophysics, 41, https://doi.org/10.1029/2002RG000123, 2003.

Sevestre, H. and Benn, D. I.: Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging, Journal of Glaciology, 61, 646–662, https://doi.org/10.3189/2015JoG14J136, 2015.

820 Sinergise Ltd.: https://apps.sentinel-hub.com/eo-browser/, last accessed: 2020-08-26, 2020.

Tadono, T., Nagai, H., Ishida, H., Oda, F., Naito, S., Minakawa, K., and Iwamoto, H.: Generation of the 30m-mesh Global Digital Surface Model by Alos Prism, ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B4, 157-162, https://doi.org/10.5194/isprs-archives-XLI-B4-157-2016, 2016.

Tajik telegraph agency: В Таджикистане стихия нанесла ущерб местным жителям, разрушив мост и 10 домов, date of access:

825

815

USGS: Declassified Intelligence Satellite Photographs, Factsheet 2008–3054, https://pubs.usgs.gov/fs/2008/3054/, date of last access: 26.08.2020, 2008.

USGS: USGS Landsat 8 Factsheet, 2013.

USGS: https://www.usgs.gov/faqs/what-are-best-landsat-spectral-bands-use-my-research?qt-news\_science\_products, date of last access: 03.02.2021, 2020.

830

2020-08-26, 2016.

Wikipedia: Tojikobod, https://tg.wikipedia.org/wiki/%D0%A2%D0%BE%D2%B7%D0%B8%D0%BA%D0%BE%D0%B1%D0%BE% D0%B4, date of last access: 26.08.2020, 2017.

Williams, M. W. and Konovalov, V. G.: Central Asia Temperature and Precipitation Data, 1879-2003, Version 1. Lyakhsh station., https://doi.org/10.7265/N5NK3BZ8, last accessed: 2020-08-06, 2008.

Schurr, B., Ratschbacher, L., Sippl, C., Gloaguen, R., Yuan, X., and Mechie, J.: Seismotectonics of the Pamir, Tectonics, 33, 1501–1518, https://doi.org/10.1002/2014TC003576, 2014.