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The Cryosphere Discussions

Brief communication: A ~50 Mm^3 ice-rock avalanche on 22 March 2021 in the Sedongpu valley, southeastern Tibetan Plateau

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Abstract. On 22 March 2021, a ~50 M m^3 ice-rock avalanche occurred from 6500 m asl in the Sedongpu basin, southeastern Tibet. The avalanche transformed into a highly mobile flow which temporarily blocked the Yarlung Tsangpo river. The avalanche flow lasted ~5 minutes and produced substantial geomorphological reworking. This event, and previous ones from the basin, occurred concurrently with, or shortly after recorded positive air temperature anomalies. The occurrence of future large mass flows from the basin cannot be ruled out, and their impacts must be carefully considered given implications for sustainable hydropower and associated socioeconomic development in the region.

1 Introduction

Catastrophic mass flows originating from the mountain cryosphere can cause hazard and risk cascades that result in widespread loss of life, destruction of property, and significant geomorphological reworking (Haeberli et al., 2004; Jacquemart et al., 2020; Kääb et al., 2021; Shugar et al., 2021). Sometimes the mass flow's path can cross international borders making them complex events to prepare for, and for managing their post-event geomorphic legacy (Evans et al., 2021). Exploring the evolution of such events is important for constraining likely triggering and conditioning factors and the nature of the mass flow process chain (e.g. for improving numerical models), and for considering the lens through which loss of human life and economic impacts should be evaluated (Evans et al., 2021; Kääb et al., 2021).

Cryospheric hazards occur frequently in the monsoon-influenced Himalayas, including the southeastern Tibetan Plateau (Kääb et al., 2021; Zheng et al., 2021), a region which hosts temperate glaciers that are typically more sensitive to climate change than glaciers on the Plateau interior (Wang et al., 2019) and which contains high topographic relief conducive for the development of hazard cascades (Tong et al., 2019). The region has undergone accelerated mass loss and areal reduction of glacier extent in the past two decades (Bolch et al., 2019) and the rate of regional atmospheric warming is above the global

https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

average (Yao et al., 2019). The region has also experienced a series of high-magnitude ice-rock avalanches, glacier detachments, and glacial lake outburst floods (GLOF) in recent decades (Tong et al., 2019; Veh et al., 2020; Kääb et al., 2021; Zheng et al., 2021). Furthermore, the region is the focus of considerable investment by the People's Republic of China (PRC), including the construction of the high-speed Sichuan-Tibet Railway (anticipated completion 2030), with development of its attendant economic corridor, and the planned construction of new, large-scale hydropower projects to serve an increasing regional and international demand for electricity. Indeed, trans-border hazards of cryospheric origin are of significant concern across High Mountain Asia, particularly when combined with the often rapid changes in both exposure and vulnerability to these geohazards (Shugar et al., 2021).

The Sedongpu basin (29.80° N, 94.92° E) in Nyingchi prefecture, PRC, has a history of large avalanches and low-angle glacier detachments which have transformed into powerful debris flows in the southeastern Tibetan Plateau (Tong et al., 2019; Chen et al., 2020; Wang et al., 2020; Kääb et al., 2021). The basin has a total area of 67 km^2 and ranges from a maximum elevation of 7294 m asl at Gyala Peri peak to a minimum of ~2750 asl m at its confluence with the Yarlung Tsangpo, a major tributary of the Brahmaputra River (Fig. 1a,b). The Randolph Glacier Inventory (V6.0) identifies 18 glaciers covering a total of ~17 km2 in the basin (RGI Consortium, 2017), which are nourished by snow, ice, and debris from very steep mountain flanks. Analysis of historic satellite imagery has revealed evidence of mass flow activity in the basin (Kääb et al., 2021) and at least 11 mass flows originating in the basin have partially or entirely blocked the Yarlung Tsangpo in past decade (Tong et al., 2019; Chen et al., 2020). The basin has recently experienced large ice-rock avalanches with a total of ~50 Mm^3 on October 2017 and into 2018, and the detachment of the tongue of Sedongpu Glacier in two separate events with a total of ~130 Mm^3 on 17/18 October and 29 October 2018 (Kääb et al., 2021). Both detachments in 2018 transformed into debris flows; the earlier detachment blocked the Yarlung Tsangpo for ~60 hours, and the rapid rise in upstream water level damaged or seriously threatened roads, power lines, hydropower stations, and other riverside infrastructure and prompted relocation of more than 6,000 local residents (Chen et al., 2020).

In this brief communication we reflect on the large ice-rock avalanche that originated in the Sedongpu basin on 22 March 2021 which, similar to past events, also temporarily blocked the Yarlung Tsangpo. We utilise *in-situ* field investigations, high-resolution satellite imagery and digital elevation models (DEMs) of difference, seismic records, and meteorological data to analyse the evolution of the event and its impact, discuss potential drivers, and briefly reflect on implications for the sustainable development of the region.

2. Data and Methods

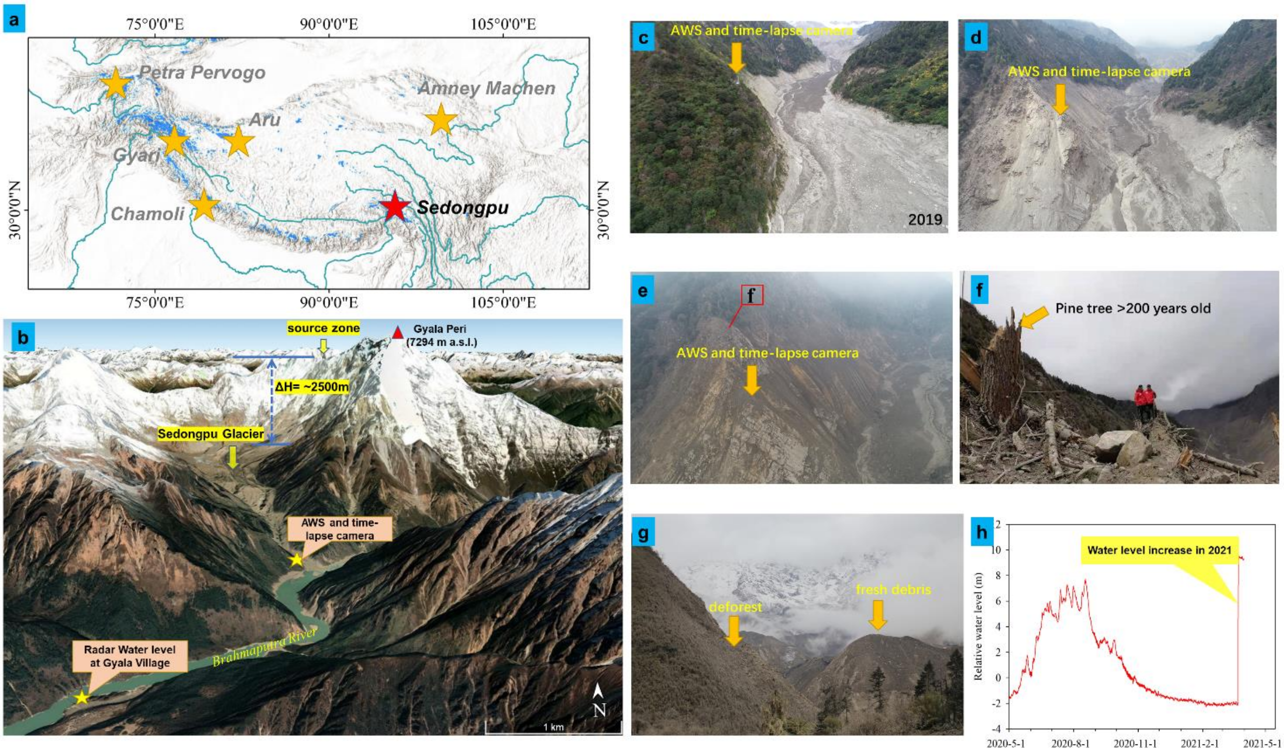
The basin's recent event history led to the installation of time-lapse optical/thermal cameras and an automatic weather station (AWS) at the exit of the basin in September-October 2019 (3 hours interval transmitted by the Inmarsat maritime satellite system) for the purpose of obtaining photographic and meteorological evidence of future mass flows and their timing, and a Campbell CS477 radar-based water level monitoring system at Gyala, which is located on the Yarlung Tsangpo ~6 km

https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

upstream of the exit of the Sedongpu basin (Fig. 1b) to provide early warning and a real-time (10 min interval) record of water level and, by implication, flow impedance in the case of future blockages. We used a DJI Phantom 4 drone to obtain aerial photographs of the basin in October 2019 (i.e. pre-event) and on 25 March 2021 (post-event), and used these imagery to document geomorphological modification of the landscape around the basin outlet (Fig. 1c-g).

Vertical seismic waveforms (10 Hz) from long-period seismographs recorded at Nyingchi station, ~60 km away from the Sedongpu basin, were used to determine the start time of the March 2021 event and track its evolution. In addition, we used United States Geological Survey (USGS) seismic and meteorological records from monitoring stations at Nyingchi, Bomi (~80 km distance) and Milin (~80 km distance) to analyse the regional tectonic and climatic context of the event.

We used pre- and post-event 0.5 m-resolution tri-stereo optical Pléiades images (Pléiades-1A on December 30 2018 and Pléiades-1B on April 30 2021, respectively) to establish the source location of the avalanche, and used high-resolution (1 m) DEMs to establish the volume and size distribution of the initial detachment and quantify net elevation change along the immediate flow path. The DEMs were derived from tri-stereo images by using PCI Geomatica software (Banff sp4) with the OrthoEngine module based on the photogrammetry principle. A sufficient number of Ground Control Points and Tie Points were also automatically collected to improve the computed math model in OrthoEngine module. In the module, the Semi-Global Matching (SGM) algorithm was used to match pixels. And the implementation of SGM is done by image-matching along epipolar lines. We used the *demcoreg* Python package to refine horizontal and vertical alignment of the DEM data (Shean et al., 2020); the final products had a relative vertical accuracy of 0.51 ± 4.1 m over stable ground (Fig. S1).



https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

Figure 1. Overview of the Sedongpu basin and the powerful destruction by 2021 ice-rock avalanche. **(a)** location of Sedongpu basin and the recent reported massive glacier detachments and ice-rock avalanches in High Mountain Asia. **(b)** ©Google Earth image (images on 2017-12-14, @CNES/Airbus and Maxar Technologies) showing topographic condition of the Sedongpu basin, the location of ice-rock falling region and the ground-based observations (yellow stars). **(c)** photo taken on October 2019 showing the 10-m high monitoring station where was about 150m above the valley bottom, **(d-g)** photos taken on 25 March 2021 showing mass flow-overtopped hill where the monitoring station was installed, the dark fresh debris deposition and deforest region near the glacier terminus, **(h)** the sudden water level rising by the Brahmaputra River blockage on 22 March 2021.

3. Results and Discussion

3.1 Field observations of March 2021 avalanche and river blockage

The last automatic data transfer from our monitoring system at the outlet of Sedongpu valley (Fig. 1b) occurred at 21:30 PM on 22 March 2021, whereafter the data feed became inactive. Shortly thereafter our water level sensor at Gyala village sent an automatic water level warning due to a sudden 2.2 m increase in river stage between 23:50 PM on 22 March and 00:00 AM on 23 March (Fig. 1h). The water level continued to increase at a rate of 0.6 - 0.8 m/hour and rose by a total of 11 m before stabilising at around 18:00 PM on 23 March (Fig. S2). Both data streams (or sudden lack of) implied the blockage of the Yarlung Tsangpo, likely by a large mass flow event, and were useful for constraining its timing.

We undertook a field visit to area on 25 March 2021 and found evidence that a mass flow from Sedongpu basin had overtopped the 200 m-high hill at the basin outlet, destroying the combined AWS-time lapse camera monitoring station and stripping the surrounding slope of vegetation (Fig. 1d-f). This included 200 year-old pine forest, thereby providing insight into the minimum return period of an event of such magnitude from this basin. By applying a simple frictionless point mass model of $u = \sqrt{2hg}$ (Iverson et al., 2016) and assuming a runup height (h) of 200 m, and g = 9.81 m/s^2, we estimate that a flow velocity (u) of around 60 m s^{-1} (~225 km/h) is required to achieve run up / superelevation to the height required for moraine overtopping. Post-event field observations showed the valley bottom to be covered by fresh, water-rich debris which was in the process of dewatering, and widespread destabilisation of valley flanks along the flow path (Fig. 1g).

Examination of the seismic record at Nyingchi station reveals the onset of a clear ground-shaking event at 23:41 PM on 22 March (Fig. 2a). The seismic waveform has the typical characteristics of a landslide because it lacks the clear P- and S-wave arrival times typical for earthquakes (Ekström and Stark, 2013). The waveform suggests that the avalanche-mass flow lasted ~300 seconds and consisted of an initial phase (lasting 100 s) exhibiting a high-amplitude signal which we infer as representing the detachment and downslope passage of the initial avalanche, followed by a ~200-second waveform with a weaker amplitude, which most likely reflects the passage of the continuous mobile avalanched mass flow through the Sedongpu basin and its outlet valley. Based on the duration of the seismic waveform and known distances (~11 km), we estimate that the mean velocity

https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

of the whole avalanche-mass flow reached ~37 m s^{-1} (~132 km/h). If the avalanche material runout the Sedongbu basin within the first 100 second, the mean avalanche velocity can reach as high as ~110 m s^{-1} (~396 km/h). These observations and inferences were corroborated by local people at Gyala village, who report hearing a continuous, 'loud' sound originating from the direction of the Sedongpu basin (pers. comm.).

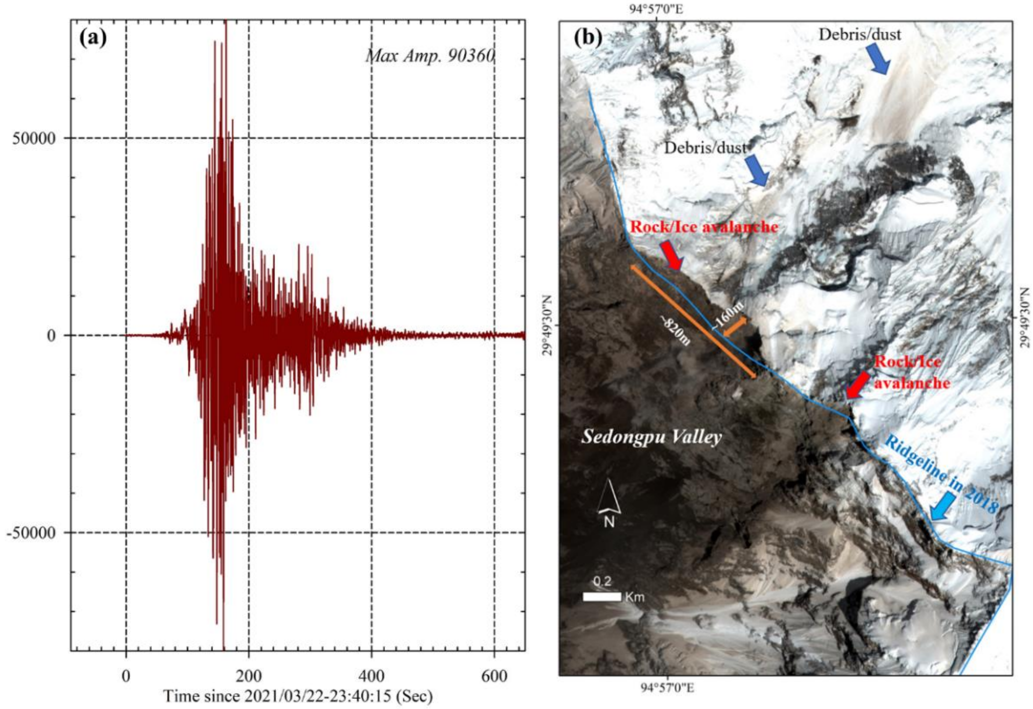


Figure 2. (a) Seismic waveform recorded at the Nyingchi station, 60 km away from Sedongpu basin starting 23:40:15 March 22 2021 and **(b)** the Pléiades image on 30 April 2021 showing the headward migration of the mountain ridgeline due to mass loss associated with the March 2021 ice-rock avalanche.

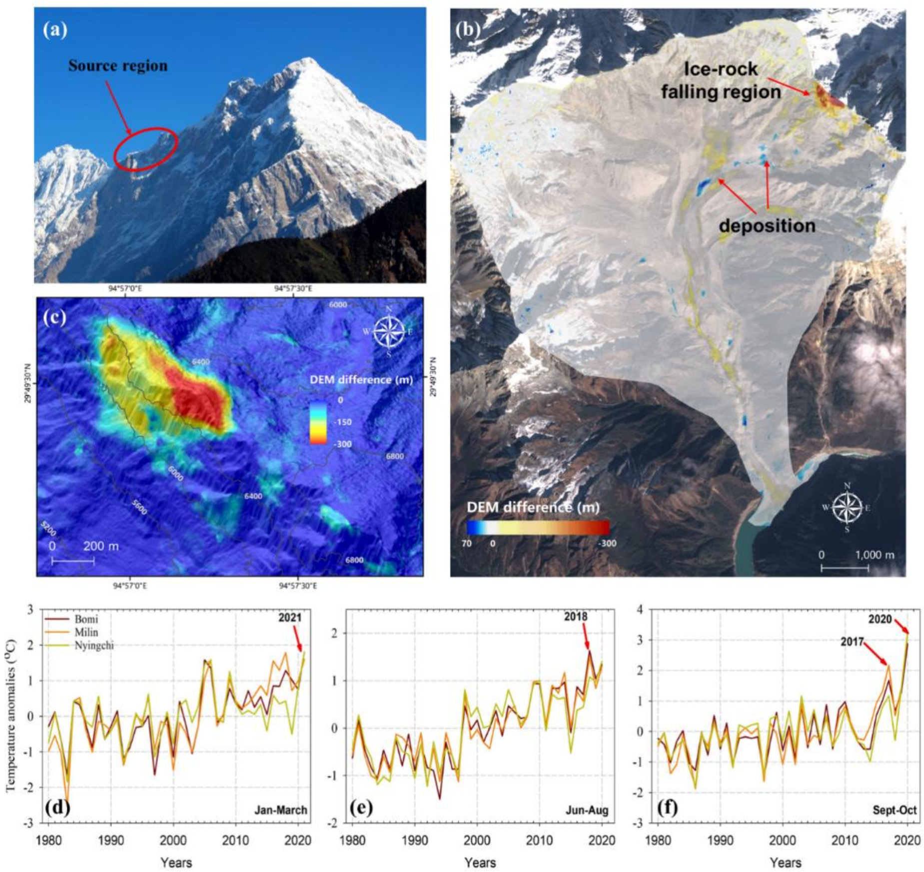
3.2 Avalanche source, magnitude and landscape change

The comparison of 0.5 m-resolution Pléaides satellite orthophotos (dated 30 December 2018 and 30 April 2021) and field investigation revealed that the avalanche originated from the western flank of a ridge that extends north from Gyala Peri (Fig. 2b and Fig. 3a). The elevation difference between Pléaides -derived DEMs reveal that about ~50.0 ± 1.5 Mm^3 of ice and rock detached from the mountain ridge (Fig. 3b,c), and we assume that the majority of this was released in the March 2021 event; we have not detected any large avalanching events, including those capable of transforming into a debris flow, since the October 2018 glacier detachment. The mean and maximum depth of the ice-rock avalanche was ~140 m and ~300 m, respectively, and the detachment scar spans an altitudinal range of ~6000 – ~6500 m asl. with a total 2D area of ~0.36 km^2. The avalanche caused headward erosion of the ridgeline of up to ~160 m, and ~0.8 km laterally (Fig. 2b).

https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

We posit that the avalanche contained a mixture of rock and glacier ice; a perched ice mass was on the ridgeline pre-event (Fig. S3), whilst the 'fresh' appearance of the rock face immediately beneath the ridge implies the incorporation of at least some rock debris, but we remain uncertain on the exact ice:rock ratio. Analysis of previous events in the basin imply the potential for a high proportion of avalanche rock debris (Kääb et al., 2021) and videography by the corresponding author captured in October 2019 (see supplementary video) shows ice collapse from the same source region as the March 2021 event on the mountain ridgeline, and then incorporating rock as it descends. Post-event field photographs and Pléiades orthophotos show that the March 2021 ice-rock avalanche occurred in the same vicinity (Fig. 1) and is located <0.5 km to the north of the large (17 and 33 Mm^3) avalanches which occurred in 2017 (Fig. S4 and Kääb et al., 2021).

Whilst the vast majority of the avalanche material descended downslope to the west into the Sedongpu basin, a post-event Pléaides orthophoto (30 April 2020) shows evidence of small-scale ice and rock avalanching into the adjacent catchment to the east of the ridgeline. We detect 15.1 Mm^3 of net deposition in the valley (Fig. 3b) and most of avalanched materials were widely distributed on the valley bottom, neighbouring glacier and the outlet of valley basin (Fig. S5). Such limited preservation of deposits associated with the event implies that the flow was highly mobile, an observation in line with previous events in the basin (Kääb et al., 2021) and elsewhere (Shugar et al., 2021).



https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

Figure 3. **(a)** Photo taken on December 2018 showing the source region of ice-rock avalanche near the north ridge of Gyala Peri peak. **(b)** DEM differences between Pléiades tri-stereo data acquired on 30 December 2018 and 30 April 2021 on the whole Sedongpu basin. **(c)** Zoomed DEM difference at the source of ice-rock falling region. **(d-f)** Anomalies of minimum air temperature during different season recorded by the three nearest meteorological stations (Bomi, Milin, Nyingchi), corresponding to the events that occurred in October 2017, October 2018 and March 2021.

3.3 Possible drivers for the 2021 ice-rock avalanche

The Gyala Peri region, and the southeastern Tibetan Plateau more broadly, are tectonically active. Seismic activity, a known mass movement avalanche trigger has been forwarded as a possible trigger mechanism for avalanche-driven debris flows originating from the Sedongpu valley in 2017 and into 2018 (Zhao et al., 2019). Indeed, the Gyala Peri region has experienced considerably more earthquakes compared to other nearby glacierized centres (e.g. Namjagbarwa, ~25 km distant; Fig. S6). Whilst we do not detect heightened seismic activity around the time of the massive March 2021 avalanche, it is possible that seismic activity over preceding years and decades may have been a conditioning (rather than triggering) factor. The frequent earthquakes, particularly the M6.9 earthquake on November 18 2017 and the following small magnitude aftershock (Zhao et al., 2019) near the Gyala Peri mountain, are likely to have enhanced any instabilities of both glaciers and rock masses in the Sedongpu valley, especially in the high mountain ridges where topographic amplification can occur. The eventual 2021 failure at the ridge crest is more commonly associated with earthquake triggering in historical inventories (Densmore and Hovius, 2000) although the 2021 Chamoli event, which was also aseismic, was also sourced close to a ridge crest (Shugar et al., 2021).

Meteorological records from nearby monitoring stations show a significant increase in mean air temperature and a decrease in precipitation since the early 21st century (Fig. S7a,b); the latter affects the southeast Tibetan Plateau more broadly. We found that the 2021 ice-rock avalanche, and previous ones from the basin, occurred concurrently with, or shortly after the record positive air temperature anomalies (Fig.3d-f for mean minimum air temperature, Fig.S7c-e for mean air temperature). The period January to March 2021 saw positive temperature anomalies in the range +1.6 - +1.8 °C, and which exceeded (Nyingchi, Bomi) or came close to exceeding (Milin) historical records (Fig. 3d). Similarly, in 2017 and 2020 we observe unprecedented positive temperature anomalies in the months of September and October at all three stations (+2.0 - 3.3 °C); the former coincides with the occurrence of the October 2017 ice-rock avalanche in the Sedongpu basin, whilst the record positive temperature anomalies in Autumn 2020 and late Winter-early Spring 2021 occur immediately before, and during, the period when the March 2021 avalanche occurred (Fig. 3f). In addition, the summer in 2018 was the warmest season during the past four decades. The mean air temperature during the June-August was about 0.95-1.3 °C higher than the mean average. The 2018 detachment at Sedongpu Glacier occurred under such unprecedented warmest summer and thus provide unusually high meltwater inputs for glacier detachment (Kääb et al., 2021). Our short-time AWS records near the outlet of Sedongpu also support such findings. The AWS recorded a small precipitation event (3.9 mm) in the morning of 22 March 2021, but with

https://doi.org/10.5194/tc-2021-306
Preprint. Discussion started: 8 November 2021

abnormal high air temperature (~2.5 °C) during the night-time if comparing the corresponding records on 22 March 2020 (Fig. S8).

It is well-established that climatic warming can initiate complex feedback mechanisms in high-mountain regions, including permafrost thaw and associated reductions in rock strength, and the warming of glacier beds, both of which can lead to enhanced instability and the initiation of mass movements (Falaschi et al., 2019; Shugar et al., 2021). Whilst it is difficult to directly attribute the March 2021 avalanche to atmospheric warming, it is likely that a series of factors including i) topographic disposition, ii) recent tectonic activity; iii) the detabilising influence of long-term regional warming on the mountain cryosphere, and iv) recent extreme positive temperature anomalies, leading to v) increased meltwater lubrication at the bed of perched ice masses and infiltration into the bedrock fracture network may have directly or indirectly contributed to the initiation of the March 2021 ice-rock avalanche and ensuing debris flow.

4. Conclusions and Implications

Our data and accompanying analysis provide insight into the source, process, magnitude and impacts of the massive 22 March 2021 ice-rock avalanche which originated in the Sedongpu basin and temporarily dammed the Yarlung Tsangpo river. Similar to the so-called 'Chamoli event' (Shugar et al. 2021) the March 2021 Sedongpu event occurred during an exceptionally warm period outside of the 'regular' summer ablation season. This event, and those that have preceded it (e.g. ~50 Mm^3 ice/rock avalanche during 2017-2018, and the ~130 Mm^3 glacier detachment in October 2018 (Kääb et al., 2021), reinforce the classification of the basin as a hotspot of catastrophic mass flow activity in a region that is likely to be the focus of large-scale hydropower and associated socioeconomic development in coming decades. Whilst we do not focus in detail on the impacts of the avalanche and mass flow further downstream, post-event satellite imagery reveals elevated turbidity in the Brahmaputra River at Xirang, ~200 km from the avalanche source and close to the disputed international border with India, less than 36 hours after the event, demonstrating the far-reaching, international influence of large mass flows from the Sedongpu basin in a region that is geopolitically sensitive. We suggest that ongoing ground- and remote sensing-based observation of this basin, and similar basins more widely across the southeastern Tibetan Plateau, should be a priority for the research community, as should predictive modelling to explore the influence of, for example, sustained deglaciation, permafrost thaw, and short-lived and longer-term atmospheric warming on the stability of the mountain cryosphere in this region. Finally, we emphasise the importance of targeted engagement with relevant stakeholders to ensure that hazards of cryospheric origin are considered within the remit of sustainable development, including the reduction of risk to life and property along potential mass flow pathways.

Data availability. Data are available upon request from the corresponding author. The video that shows an ice-rock avalanche in the Sedongpu basin in October 2019 is available (http://cloud.tpdc.ac.cn/f/0a022898bf2941d3bdc2/?dl=1). We utilised PlanetScope (www.planet.com) image IDs 20210310_033352_64_245d (March 10), 20210323_033244_29_2451 (23 March) and 20210324_035901_1040 (24 March) to analyse river turbidity and identify the sediment plume from the 22 March Sedongpu event in the Brahmaputra River at Xirang. Long-period seismographs were provided by the Data Management Centre of the China National Seismic Network at the Institute of Geophysics, China Earthquake Administration and are available on request. The meteorological data for Nyingchi, Bomi and Milin stations are available from Chinese Meteorological Data Service Center (http://data.cma.cn). USGS earthquake data are from https://www.usgs.gov/natural-hazards/earthquake-hazards/lists-maps-and-statistics

Competing interests. The authors declare that they have no conflict of interest.

Author contribution. All authors conceived the study and collected, processed, and analysed data. W.Y., Y.W., Z.W, B.A and G.W. carried out fieldwork, W.Y and C.Z. performed remote-sensing analyses. M.W and S.D contributed result discussion. All authors contribute to write the paper.

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