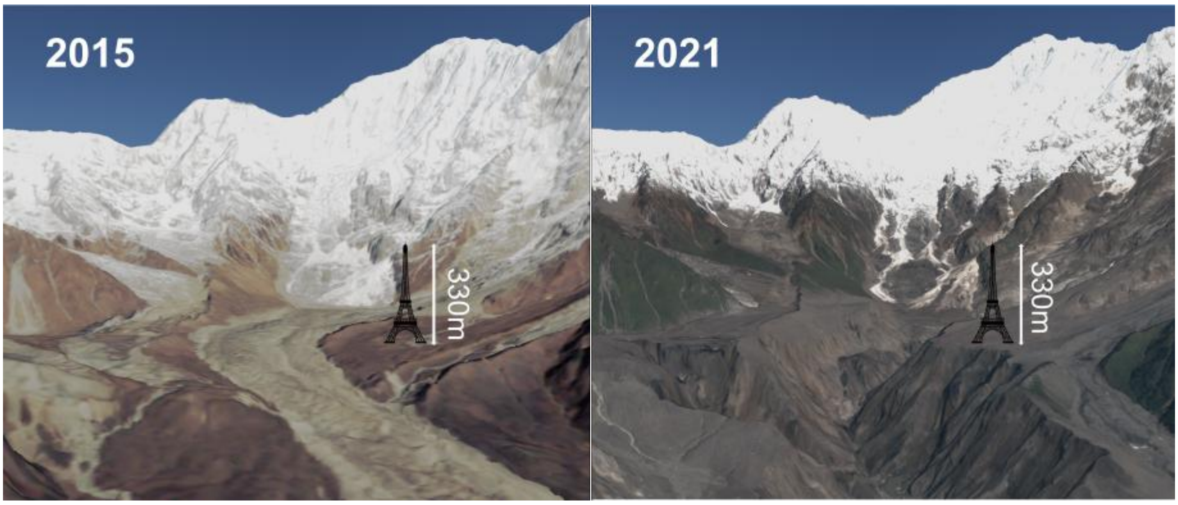
GEO9520

DEM generation at Sedongpu Glacier (SE Tibet) for debris flow volume estimation



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1 Introduction

Digital Elevation Model (DEM) generation from stereo imagery relies on the basic positioning principle that the intersection of two rays from two known sensors uniquely defines a point in space.

DEM from satellite imagery are particularly useful for glacier monitoring, often located in remote mountainous area. From retreats, advances to abrupt detachments, ice-rocks avalanches and massive erosion, glacier motions can be monitored by satellite images acquired at different times.

The Sedongpu glacier (Figure 1) is located in a remote mountainous valley of the Himalayas in SE Tibet (China). It is categorized as a low-angle mountain glacier with a 9° slope. During the time period 2015 to 2021, the glacier underwent dratic changes, evidenced by the carving a 300 meters deep canyon where the glacier tongue was previously located (see illustration on the cover page). Several ice-rock avalanches, glacier surge, detachment and massive erosion events were observed on optical satellite imagery and described in Kääb and Girod (2023) and Kääb et al. (2021).

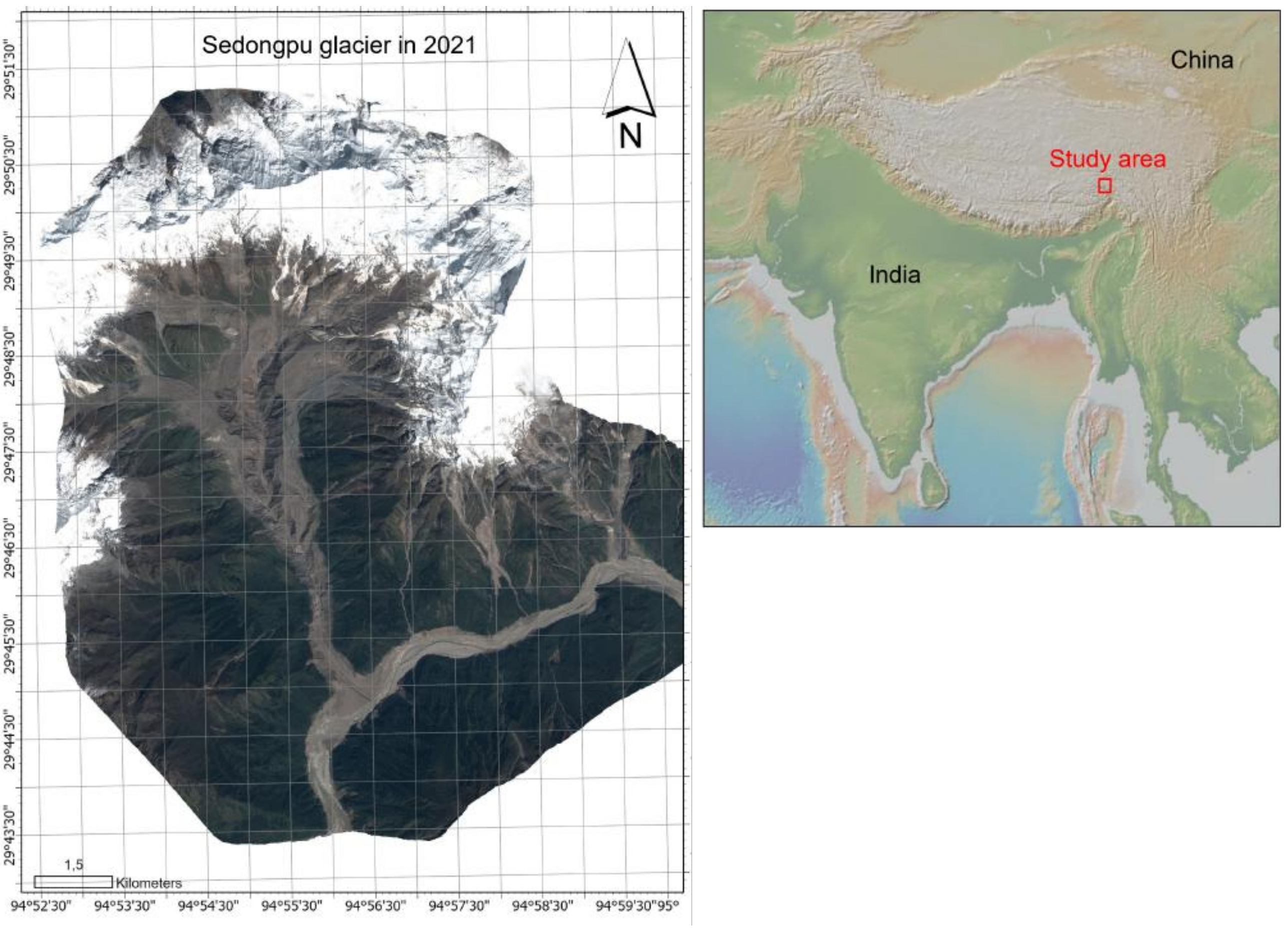

Figure 1: Orthorectified satellite image of the Sedongpu Glacier acquired in september 2021 (left, credit: Pleiades Satellite data). Location map of the study area in the Chinese Himalayas, SE Tibet (right, credit: GeoMapApp).

The overall objective of this project is to estimate the volume of the multiple ice-rock debris flows that occurred at Sedongpu glacier in the periods 2015-2018 and 2018-2021 based on optical satellite imagery. To achieve this goal, we first generate three DEMs from 2015, 2018 and 2021 satellite stereo-images. The quality of the DEM is assessed by comparison with a reference DEM for each years of interest. We also report on the production orthorectified satellite images based on the three DEMs. We compute the volume of rocks by DEM differencing. Finally, the volumes estimates of each debris flows are compared with a published study (Kääb and Girod, 2023).

2 Data and Method

2.1 Satellite optical images

We use three set of satellite stereo-images purchased from AIRBUS Defence and Space (Figure 2). The SPOT6 satellite tri-stereo images were acquired along-track on 13.11.2015 with a spatial resolution of around 6 meters for the panchromatic images. The Pleiades 1A and 1B satellite images were acquired along-track on 30.12.2018 (tri-stereo) and 19.09.2021 (stereo), respectively. Pleiades panchromatic images have a spatial resolution of around 2 meters.

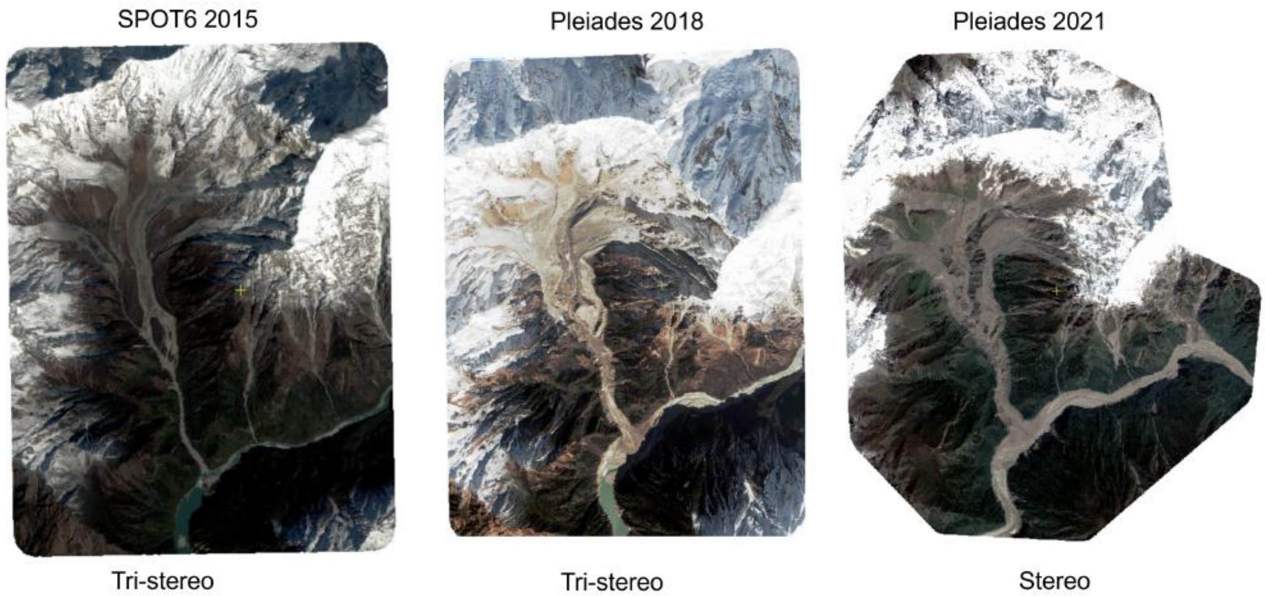

Figure 2: Stereo optical satellite images of the Sedongu glacier on 13.11.2015 (left, credit: SPOT6 satellite data), 30.12.2018 (middle, credit: Pleiades satellite data) and 19.09.2021 (right, credit: Pleiades satellite data)

2.2 Workflow

The workflow used in this project is summarized in Figure 3 and captures the main processing steps, from raw stereo-images to debris flows volume calculation.

The georeferencing step consists in defining ground control points (GCP). The transformation to epipolar geometry is an important step that reduces the search of matching pixels along only one direction. We use the Semi-Global Matching (SGM) method for parallax matching on the epipolar stereo-image pair and subsequent DEM generation. The image orthorectification process is then performed with the DEM generated for 2015, 2018 and 2021. All this steps are performed with OrthoEngine of the PCI Geomatics software suite.

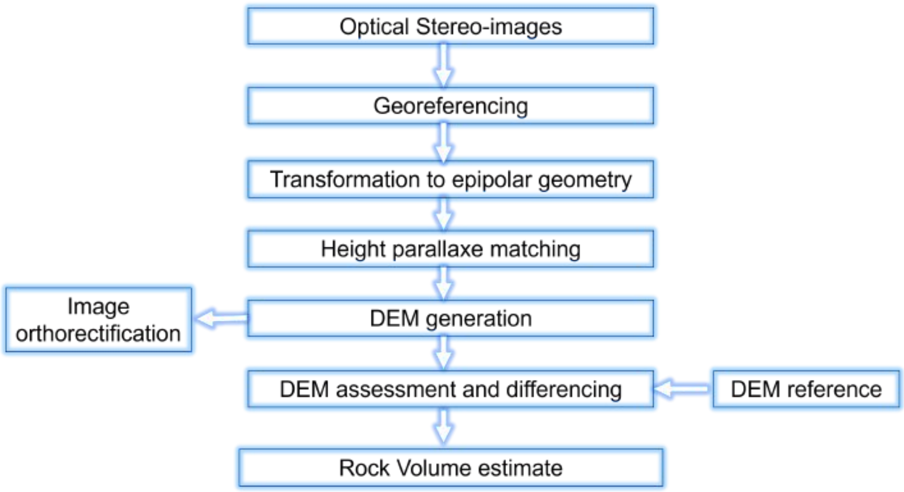

Figure 3: Workflow

The DEMs are then converted to GeoTIFF raster files and imported to intoArcGIS for differencing, spatial calculations and/or filtering operations. The provided reference DEMs for 2015, 2018 and 2021 originate from the MICMAC software.

Finally, the debris flow volume are computed with Python using the rasterIO package (https://rasterio.readthedocs.io/en/stable/).

3 Results

The resulting Digital Elevation Models (DEM) of the Sedongpu Glacier from 2015, 2018 and 2021 satellite stereo-images are shown in Figure 4 as hill-shaded surfaces with purple to red color-scale indicating low to high elevation points. At a first glance, the DEMs capture appropriately the main elements of the landscape: glacier topography, Yarlung Tsangpo river, mountain peaks. The height of the highest elevation point of the area is the Gyala Peri, culminating at 7294 m a.s.l according to Google Maps and recent scientific work (Kääb and Girod, 2023). The Gyala Peri peak is modelled at ca. 7240 m a.s.l for each of our three DEMs, highlighting a 50 meters elevation difference with the true value. Some of the steepest mountain slope appeared poorly represented and modelled as very rugged surface like in the northernmost peak in Pleiades 2018 DEM in Figure 4.

To quantitatively assess the quality of our DEMs, we use reference DEM provided by a third party to compute elevation difference maps (Figure 5) and to investigate the distribution of the differences for each years (Figure 6). We observe that the

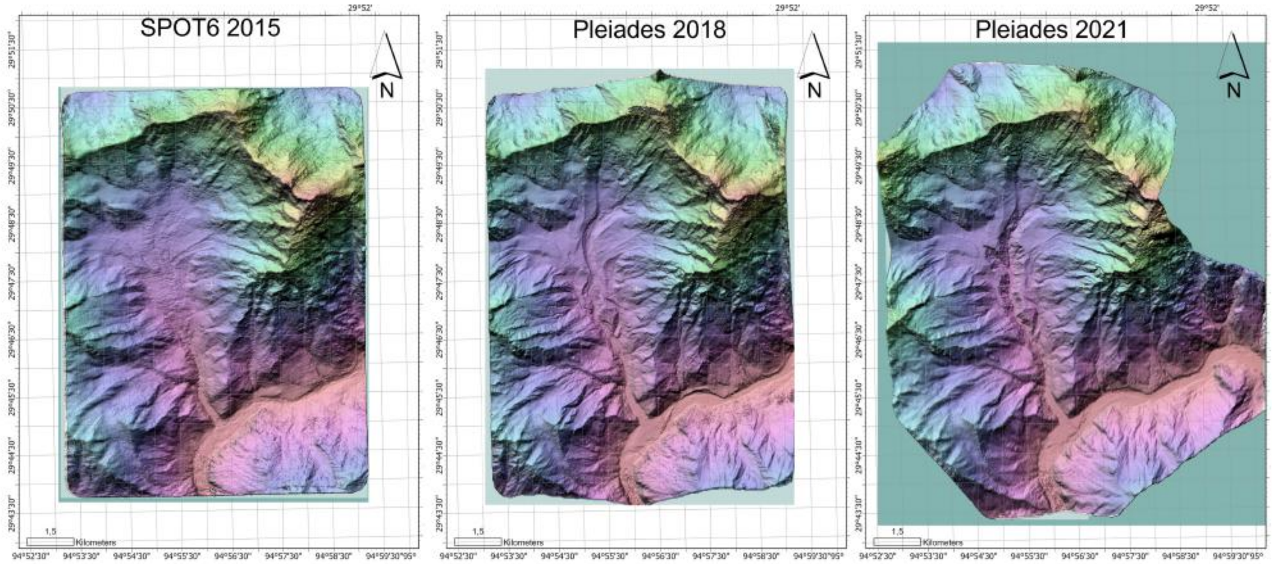

Figure 4: Digital Elevation Models of the Sedongpu valley (SE Tibet) generated from satellite stereo-images in 2015 (left), 2018 (middle) and 2021 (right).

number of pixels with high elevation ”errors” is highest for the SPOT6 data while the Pleiades 1A and 1B DEMs have equivalent lower elevations differences with the reference DEM. This is also evidenced by the distribution of the pixel values (elevation difference) where the Pleiades data have a higher peak value, centered around a median values of 1.28 and 1.68 m whereas the SPOT6 distributions is flatter and the errors values more spread (Figure 6). In all three elevations maps (Figure 5, the peaks and steepest mountain slopes have the largest errors. In contrast, the ”flat” glacier area has relatively lower elevation differences with the reference model.

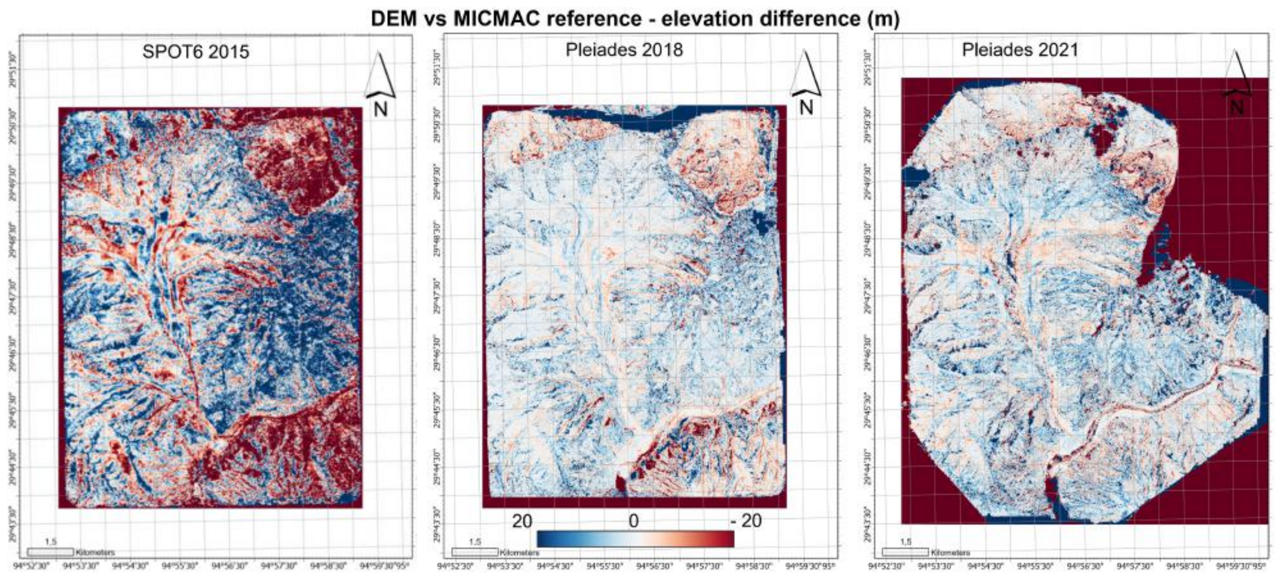

Figure 5: Elevation difference maps with respect to reference DEM for 2015 (left), 2018 (middle) and 2021 (right).

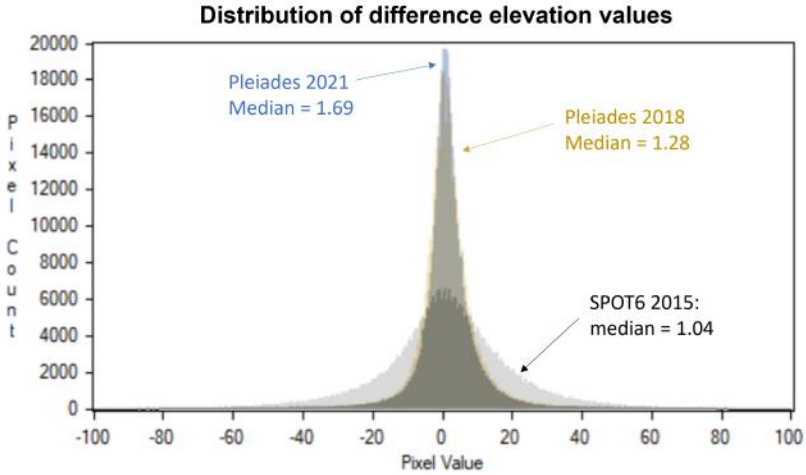

Figure 6: Distribution of elevation difference values in meters (pixel value on x-axis of the graph) with respect to reference DEMs for each year of interest.

The orthorectified satellite images are provided as a by-product of the DEM generation in Figure 7. Comparing between orthorectified and raw images (Figure 2), we observe that the Pleiades 1A (2018) image is the most rectified because it was acquired at a lower azimuth angle than the other image datasets.

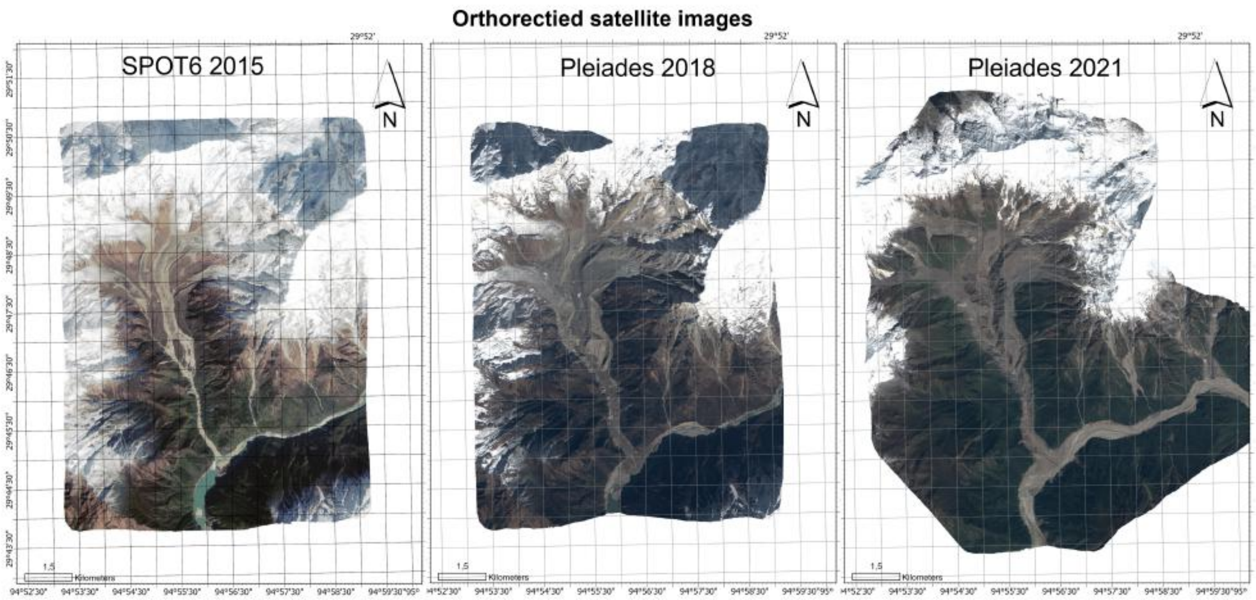

Figure 7: Orthorectified satellite images of the Sedongpu Valley (SE Tibet) for each year of interest.

Finally, the DEM difference maps are calculated at time steps 2015-2018 and 2018-2021 (Figure 8). The estimated gain or loss volume of ice and/or rock for each identified events are indicated in Figure 8, and summarized in Table 1.

In the 2015-2018 period, one can clearly identify four negative elevation difference anomalies (loss of topography) and one positive anomaly (gain of topography).

We find that two areas of ca. 2 and 1 km^2 have lost a topography of up to 130 meters near mountain crests. They likely correspond to ice-rock avalanches events on steep and unstable slopes. The negative anomaly in the valley area closely follows the shape of the tongue of the glacier, removing up to 120-130 meters of topography along a ca. 5 km section. The last "moon-shaped" negative anomaly is located along the bank of the first river meander downstream of the Sedongpu Valley. The only positive build up of topography corresponds to the fan-shaped debris damming the river.

In the 2018-2021 period, an elevation loss anomaly is located near the crest at the same location as the previous period, indicating that a similar avalanche occurred on already unstable slopes. The largest loss of topography (up to 300 meters deep!) in the glaciers, showing patterns of erosion typical of massing canyon-carving in contrast with the detachment in 2017. Finally, a positive topography around the Gyala Peri peak is identified in the period 2018-2021. This peculiar build-up near the mountain peak is discussed in the next section.

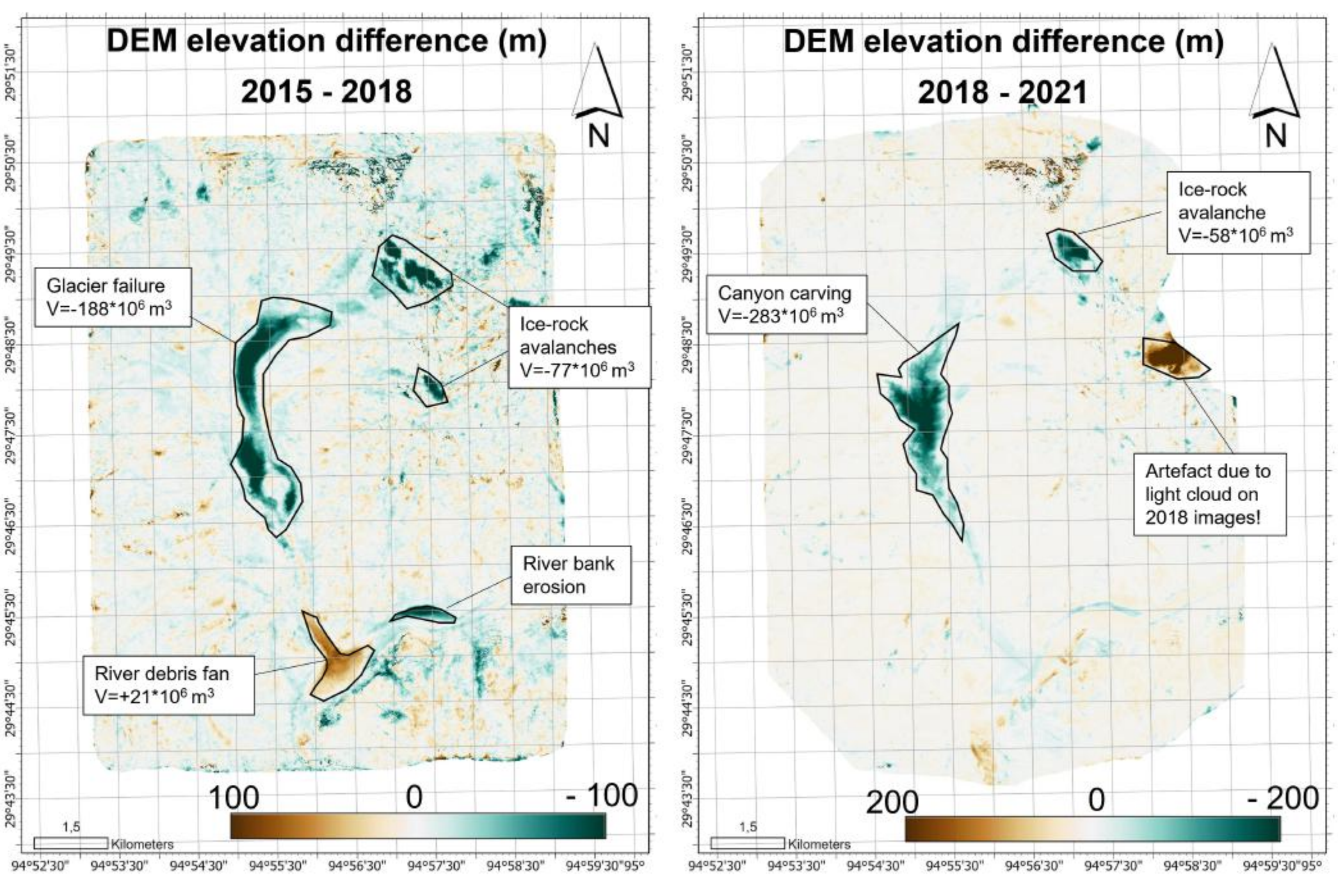

Figure 8: DEM elevation difference maps of the Sedongpu Valley (SE Tibet) for the time periods 2015-2018 (left) and 2018-2021 (right).

4 Discussion and conclusion

The SPOT6 DEM elevation difference with the reference DEM in 2015 (Figures 5 and 6) show significant deviations values that may affect the rock volume estimates. Most important elevation differences occur on the steep slopes where coregistration error are expected to have the most impact on DEM generation. This difference elevation reference map mimics closely the 2015 DEM hill-shade surface (Figure 4), further supporting that coregistration might be responsible for the elevation mismatch (Nuth and Kääb, 2011). For 2018 and 2021 DEMs, the elevation difference with reference model are roughly between 10 and -10 meters, which is negligible in comparison of the magnitude of hundreds of meters of glacier failure and massive erosion.

Considering the potential source of uncertainty of DEM from coregistration error (Nuth and Kääb, 2011), we compare our estimate with the one from Kääb and Girod (2023) in Table 1.

Event	Time period	Volume change (this study)	Volume change (Kääb and Girod, 2023)
Ice-rock avalanche(s)	2015-2018	-77.10^6m^3	-50.10^6m^3
Glacier failure	2015-2018	-188.10^6m^3	-174.10^6m^3
Debris fan (river)	2015-2018	$+21.10^6m^3$	-
Massive glacier erosion	2018-2021	-283.10^6m^3	-279.10^6m^3
Ice-rock avalanche	2018-2021	-58.10^6m^3	-50.10^6m^3

Table 1: Volume estimate of debris flows from various events occurring in the Sedongpu Valley (SE Tibet) in the period 2015-2021

The volume estimate of the two largest events (glacier detachment in 2017 and massive erosion in summer 2021) are equivalent in our calculation and the one reported in Kääb and Girod (2023). The mismatch (12.10^6m^3 for glacier detachment and 4.10^6m^3 for canyon carving) is within the volumes (or uncertainties) obtained from the elevation differences with the reference DEMs (Figures 5 and 6). The ice-rocks avalanches volume estimate is also equivalent for the period 2018-2021 but significantly differ for the period 2015-2018 with ca. 25% increase of rock volume. Again the coregistration error for 2015 DEM (Figure 5 has a large impact on steep slopes where avalanches occur in the Sedongpu area. We therefore expect large variations in the estimate of ice-rock avalanches in the period 2015-2018 due to uncertainty of the 2015 DEM. Finally, the positive topography build-up near the Gyala Peri peak observed between 2018 and 2021 (Figure 8) is due to a light cloud cover on the Pleiades 1A images (Figure 2) barely visible to the naked eye. Light cloud cover typically hinder DEM generation from optical stereo-images.

References

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