First insights into the Chamoli disaster, February 7 2021

UPDATED VERSION FEB 20, 2021 (Updates see page 9)

Purpose and scope

This document summarizes first insights on the processes that caused a massive flood of the Dhauliganga river in the Chamoli district, Uttarakhand, India on February 7 2021. The data and information presented here comes mainly from communications within an international ad-hoc working group of scientists from the GAPHAZ[1] community and Indian scientists. This is a working document, updates are released when more information becomes available. All facts presented here are of preliminary nature and subject to further investigations.

Processes causing the flood

Rock/ice avalanche

In the morning of February 7, 2021 a major rock/ice avalanche detached at an elevation of about 5,600 m a.s.l. from a north facing slope northeast of Trisul Peak in the Nanda Devi massive (detachment location: 30.375°N, 79.730°E). After this avalanche, a massive flood occurred in the Rishi Ganga / Dhauliganga river, reportedly causing loss of life and the destruction of two hydropower plants and other infrastructure, such as bridges and roads. Figure 1 gives an overview of the situation.

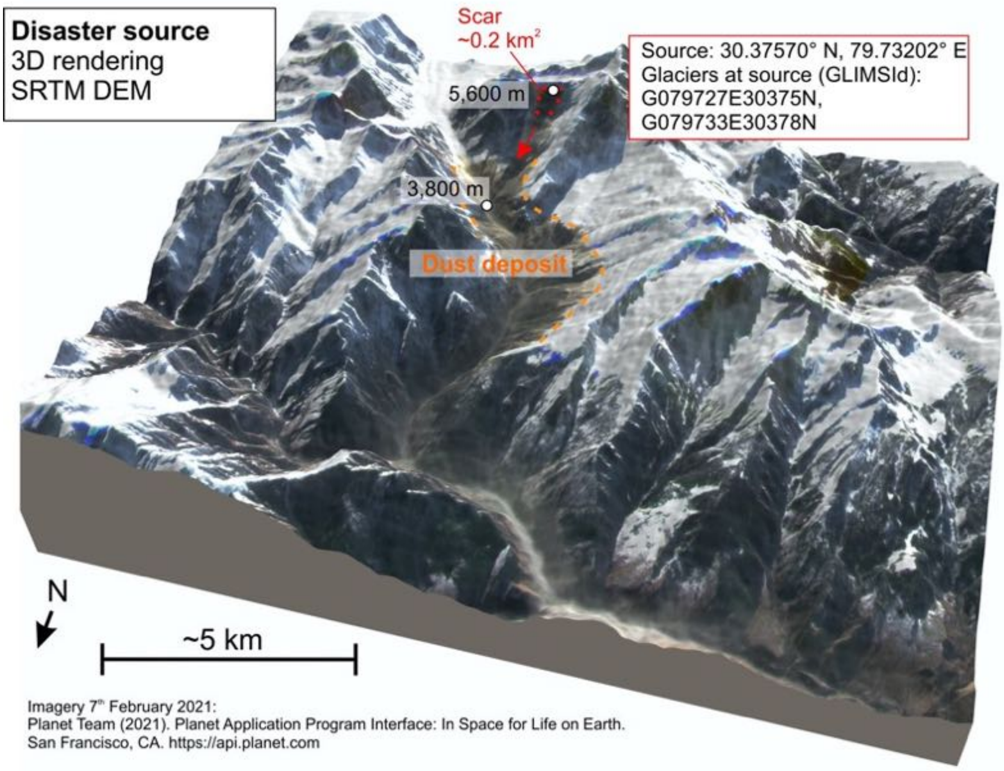

Figure 1: Overview of the site of the rock ice avalanche from Feb 7, 2021 (courtesy of Scott Watson)

[1] Glacier and Permafrost Hazards in Mountains (GAPHAZ): A Scientific Standing Group of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA).

Figure 2 shows Planet Labs imagery of the avalanche detachment zone from the day before and minutes (to maybe an hour) after the event. Another image acquired at 10:31 AM IST already shows the failure and a dust cloud, but the hydropower plant at Tapovan still intact, while in the image acquired at 10:58 AM IST it is already destroyed. This indicates the avalanche occurred probably shortly before 10:31 AM IST.

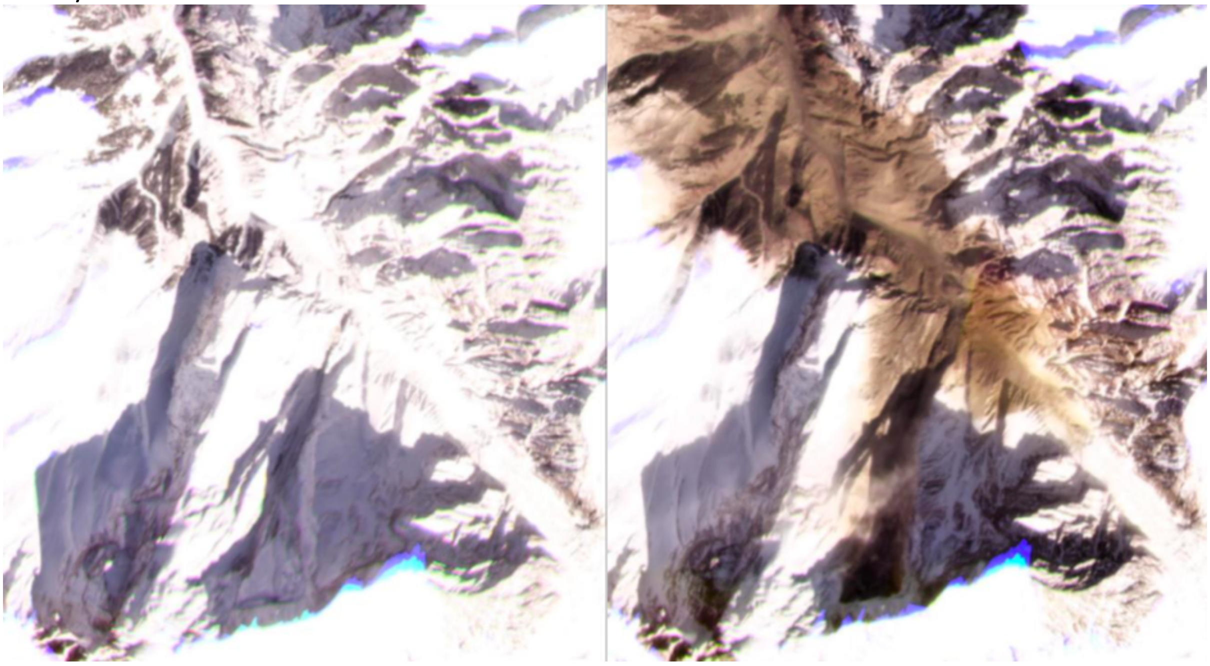

Figure 2: Planet Labs imagery from Feb 6 (left) and Feb 7, 10:58 AM IST (right). The detachment zone of the rock/ice avalanche and dust deposits are clearly visible on the image to the right. (Source: Planet Labs, courtesy of Andreas Kääb and Dan Shugar)

Post event imagery shows large areas covered by dust from the avalanche (cf. Figure 2, right) indicate the involvement of bedrock in the landslide. It is yet unclear if the bedrock material has been involved due to a collapse of the glacier or if the failure happened mainly in the bedrock and entrained the overlaying ice. *Update Feb 20: It is now known that failure happened deep within the rock, glacier ice was most probably only entrained with the collapsing block of (bed)rock, see Updates February 20, 2021, below.* Further, a crack is observed to have formed at the upper end of the detachment zone between 2016 and 2017 (Figure 3). The opening of this crack is documented with satellite imagery from September 2020 to the days prior to the event, likely with increasing speed (Figure 4). The width of this crack of about 50 m is remarkable.

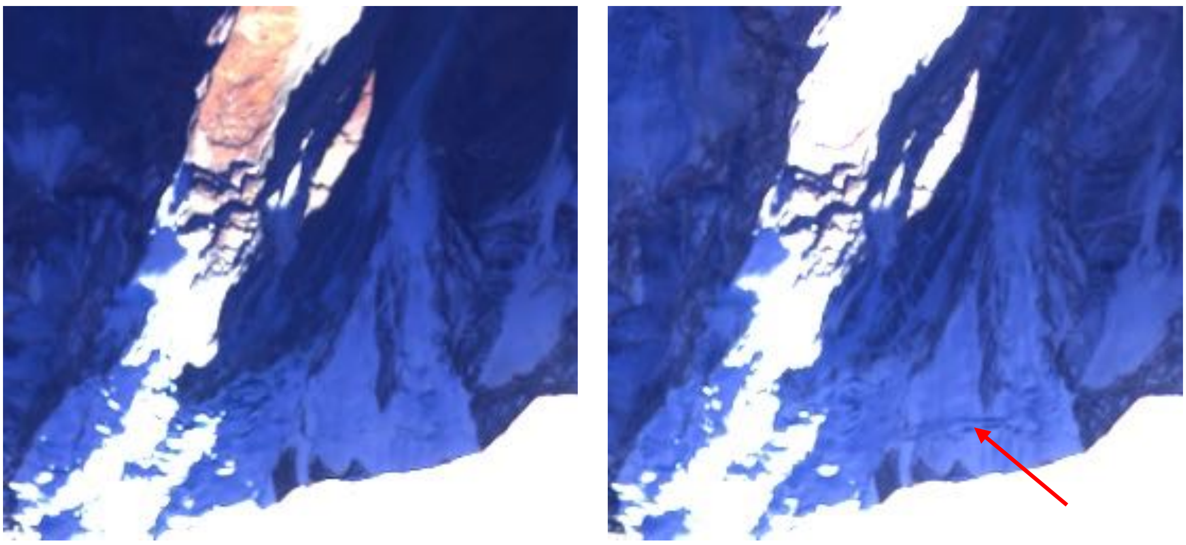

Figure 3: Sentinel-2 imagery from Nov 28, 2016 (left) and Nov 28, 2017 (right). The opening of a crack is visible in the 2017 image (red arrow) at the upper end of the detachment zone Feb 2021 avalanche. (Source: Sentinel-2 ESA, courtesy of Silvan Leinss).

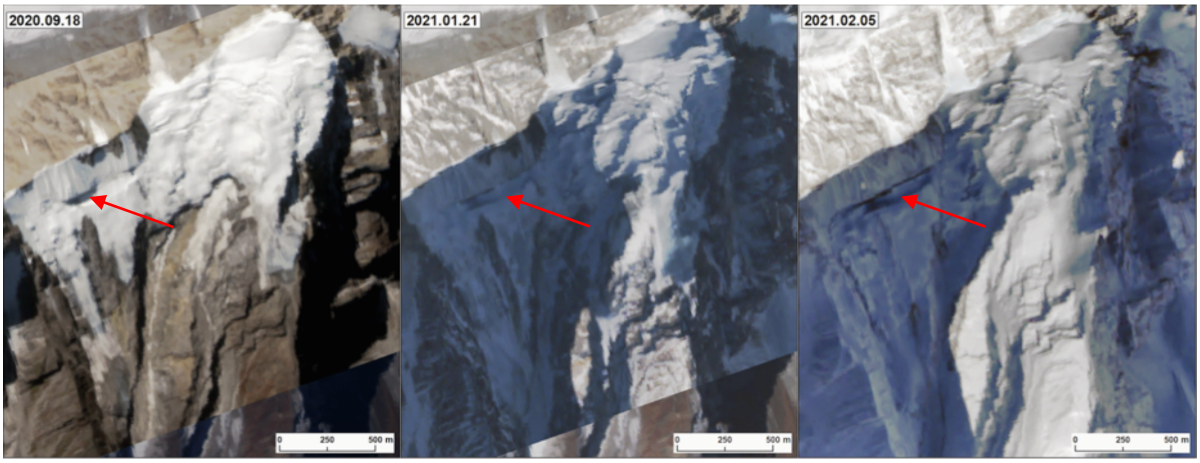

Figure 4: Crack (red arrows) at the source of the February 7, 2021 avalanche documented with images from various sources. (Courtesy of Mikhail Dokukin).

At the elevation of the crack, about 5,600 m a.s.l. continuous permafrost is expected. However, in connection with glacier cover and/or firn, polythermal conditions are common at the ice-rock interface, with some unfrozen parts at the glacier bed (i.e. presence of liquid water possible) and other parts with warm permafrost, where the ice is frozen to the bedrock with temperatures < 0°C but close to thawing. Crevasses in the ice can also advect heat to the underlying rocks, especially if cracks and clefts are present.
Interpretation updated Feb 20, see below.

A high resolution satellite image of unknown date, but acquired before 2016, clearly shows a slope-parallel, downward layered rock structure underneath the detached ice masses (Figure 7). Such a structure favors the detachment of slope-parallel rock slabs, in particular when water enters the contact layers of the slabs or when ice at this contact layers is melting.

Figure 5: High resolution image of unknown date (prior to 2016), showing a slope-parallel, downward layered rock structure. Detachment zone of the 2021 avalanche indicated by black line. (Source: www.bing.com/maps, courtesy of Silvan Leinss).

Based on this information, we currently think a failure within the bedrock is the most likely trigger of this avalanche. *In the meantime confirmed, see update Feb 20, below.*

As indicated in Figure 1, the failing mass covered an area of around 0.2 km^2. Assuming an average depth of the failing mass of 5 – 50 m, this results in a total avalanche volume of 1 – 10 million m^3, respectively. Analyses of pre and post event topography will help to better constrain this volume estimate.
Update Feb 20: Current estimates yield a total avalanche volume of 25 million m^3, composed by ca. 20 million m^3 of rock and ca. 5 million m^3 of ice, see Updates February 20, 2021, below.
It should be noted that further material (solid and liquid) is likely to have been mobilized for the flood (see also below).

Preliminary mass movement modeling of a 2.7 million m^3 avalanche (based on the (conservative) assumption of an average depth of 10 m of the landslide mass) indicate the flow depths of > 50 m in local depressions and flow velocities of up to 75 m/sec in the initial part of the avalanche, in the steep mountain flank (Figure 6). *Update Feb 20: The previous version of Fig. 6 has been replaced by a figure from a revised modeling with the updated volume of 25 million m^3.*

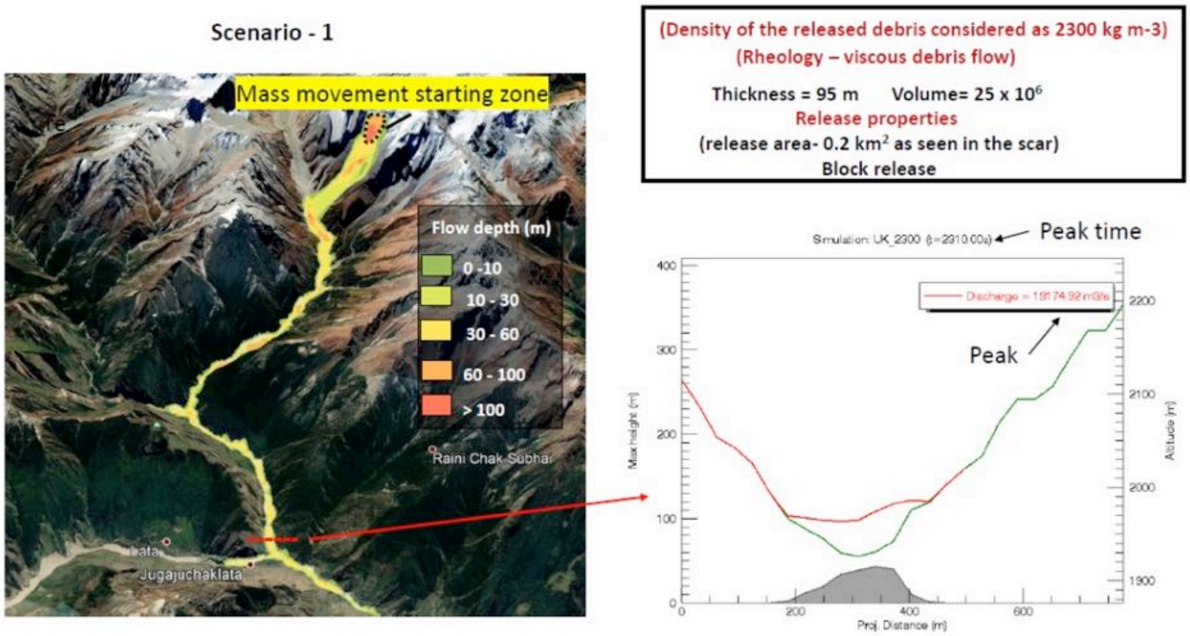

Figure 6: Reconstruction of flow depth and flow velocity with the RAMMS model, for an assumed 25 million m^3 avalanche (courtesy of Ashim Sattar).

History

Historical imagery indicates an ice or rock/ice avalanche has occurred on the neighboring glacier just east of the now collapsed glacier in 2016, between September 19, 2016 and October 3, 2016 (Figure 7). A 2017 image in Google Earth clearly shows the large deposits from this avalanche, consisting of debris with a significant amount of ice.

Update Feb 20: Satellite imagery now constrains the timing of this earlier avalanche to between September 19 and September 26, 2016. New findings on the state of the deposits of the 2016 avalanche in the moment of the recent Feb 2021 avalanche, see Updates February 20, 2021, below.

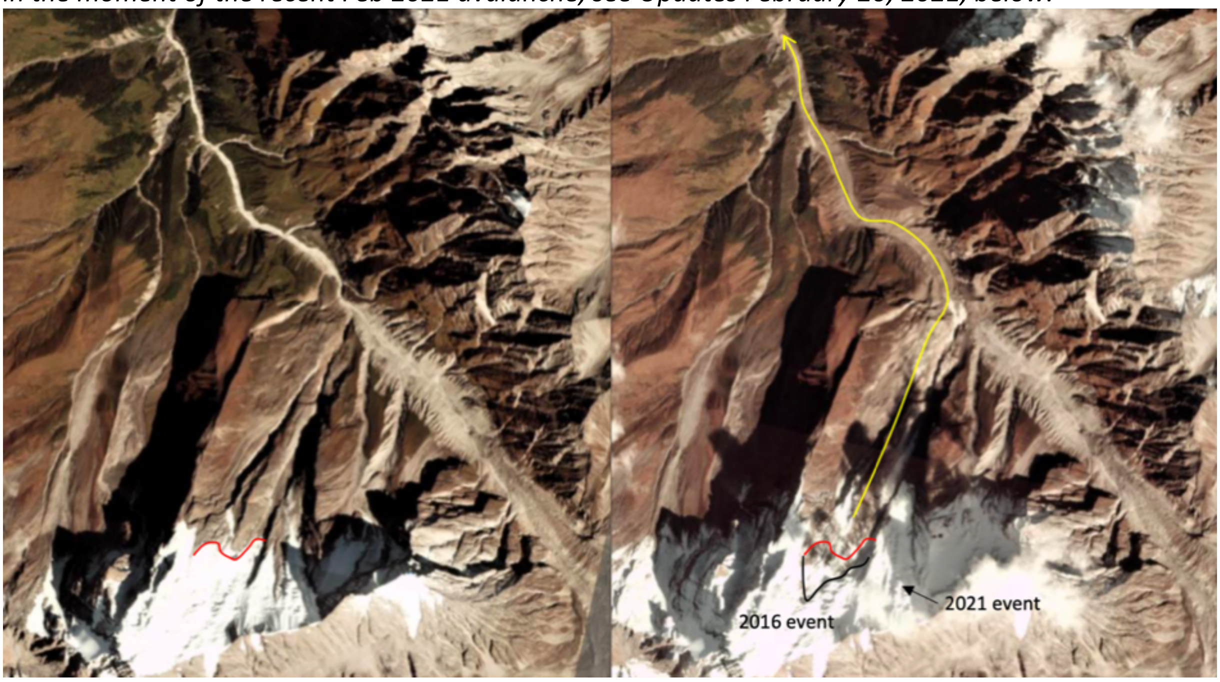

Figure 7: Evidence of a similar event on the neighboring glacier, happened between Sept 19, 2016 (date of left image) and Oct 3, 2016 (right image), detachment zone and trajectory indicated. Note the deposits in the valley in the right image. (Source: Planet Labs, courtesy of Andreas Kääb).

Flood

Several processes in relation to the avalanche form February 7, 2021 are possible, that eventually caused the massive flood in the Rishi Ganga / Dhauliganga river. The question of the origin of the flood water is currently considered as the biggest open question. Below some considerations and hypotheses.

Update Feb 20: Initial conservative estimates now give us strong confidence that sufficient water to cause the flood could have been generated from frictional melting and liquefication of ice within the avalanche and possible mobilization of water stored in (saturated) sediments. This suggests no additional sources of water were required (e.g temporary damming), although these possibilities cannot yet be definitively excluded. For details see Updates February 20, 2021, below.

Impact energy and frictional melting

The very steep avalanche trajectory, dropping around 2000 m in elevation over a distance of about 3.3 km, indicates the release of high impact energy. Along with the entrainment, most of the glacier ice of the avalanche is assumed to have melted. In addition the area was under a snow cover of unknown depth, which is as well assumed to have melted due to the frictional energy of the avalanche, as it is know from many other cases. This melting of ice and snow can have contributed large amounts of water to the runoff.

Satellite imagery suggest snowfall / low snow limit on February 3, 4, and 5, and a rapid increase of the snow line on February 6 and 7. But no direct information on precipitation amounts is available. Data from NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG) suggest only minor precipitation amounts (Figure 8), but this needs to be confirmed from on-site observations.

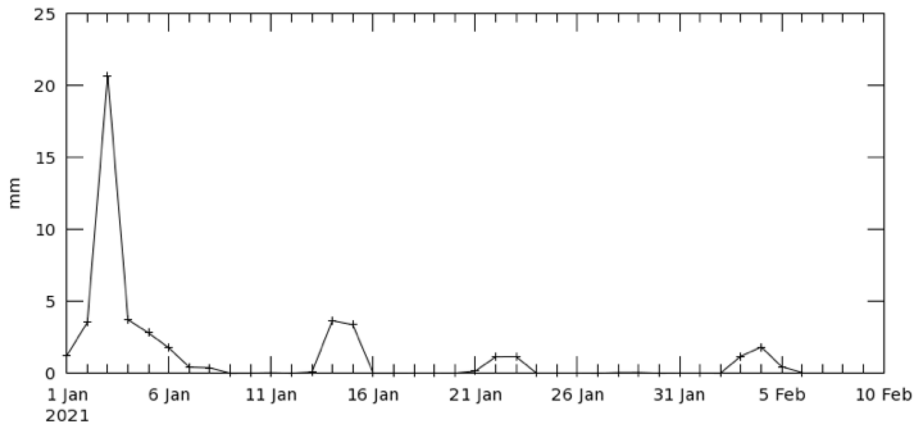

Figure 8: Precipitation history of the region. (Source: IMERG/NASA, courtesy of Simon Allen).

Mobilization of 2016 avalanche deposits

The recent avalanche has impacted the deposits of the 2016 avalanche (see above). This will have entrained sediment and debris, and possible also buried ice still present under the debris cover of these deposits. Also, it is possible that larger amounts of water are trapped under and within this sediment body, which can be mobilized if impacted and eroded. The conditions of these deposits at the moment of the avalanche impact need to be further investigated.

Update Feb 20: Deposits of the 2016 avalanche might only played a minor role as they have melted before the recent Feb 2021 avalanche, see Updates February 20, 2021, below.

In general, sediments in the sediments can be saturated with water from precipitation and/or snow melt. This is possible not only for the deposits of the 2016 ice avalanche, but for all sediment bodies which are abundant along the trajectory of the avalanche and flood. The water content stored within these depositions can be very high, in particular in fine grained sediments with high clay content.

Temporary damming (of a tributary river)
At Raini village, Rishi Ganga joins the Dhauliganga river. Upstream to his, another tributary river confluences with Rishi Ganga. It is possible that the deposits of the avalanche and/or subsequent flood caused a temporary damming at one of these tributary rivers, cf. deposits and back flow at these confluences in Figure 6 above. In that case, a failure shorty after daming could have led to a flood wave, or to a critical temporary lake with a potential for failure in case the dam is still in place. A tweet from Asian News International says they did an aerial survey and found a lake that has formed in the valley and burst later, causing the damages: https://twitter.com/ANI/status/1358717190946447360?s=20. This is not confirmed to us yet, but within the range of possibilities.
Also temporary damming within the main channel of the river is possible. Post event imagery shows some features which could be the remnants of temporary dams, but this would need to be confirmed by other data.
Due to the lack of evidence of any glacial lake present along the avalanche trajectory, we currently exclude an outburst flood from a glacial lake (GLOF) as speculated in earlier media coverage.
Updates Feb 20: Involvement of a temporary lake in the flood event from February 7 is very unlikely. However, a temporary lake formed at the location indicated in Fig. 6 as a consequence of this event, dammed by deposits of the mass flow. This is a source for subsequent hazards, see Updates February 20, 2021, below.

River runoff accumulating in a fast moving wave
Considering the high speed of the avalanche it is well possible that the water of the river is pushed forward in front of the avalanche and accumulates to a major flood wave. From the point in the valley below the avalanche source zone the river stretches over 13 km to the village of Raini and another 6 km from Raini to the hydropower plant at Tapovan. In combination with the high velocity of the avalanche this could well lead to a large accumulation of river water in such a front wave.
New calculations and estimates show, that this would only provide a very minor contribution to the flood, see Updates February 20, 2021, below.

Recommendations for field investigations and data needs

We have learned the field investigations are now running. As currently many persons seem to be on the ground in areas of potential follow-up processes. For instance, detailed monitoring of the detachment zone and the avalanche deposits are needed (see also below). Further, there is a possibility of slope collapses along the river, in case erosion during the flood has undercut the slopes.

Update Feb 20: Such collapses could lead to temporary damming of the rivers, followed by high discharges in case the dams fail. If not done already, we recommend to establish a dense network of persons surveying the situation and able to emit alarms for evacuation in case needed from the avalanche site and along the entire stretch of the river.

Based on the first insights, mostly derived from satellite data, as presented above, the following points could be clarified in such field visits:

- Any indication of temporary lakes, dammed by mass movement deposits?
- A detailed overview of the detachment zone is not only of interest for the reconstruction of the avalanche, but also as critical processes could be happening. Such a release of mass leads to major changes in the stress field of this rock face, so first there is a (probably rather small) chance for a second event. Certainly some minor after events are ongoing. But this is

something that should be looked at also on a long term perspective. Info on after-event activity and aerial photography of the detachment zone, showing the rock structure of the failure zone would be highly appreciated.

- Investigations of the deposits at the foot of the avalanche slope. There must be huge amounts of material now (rock, debris, ice, water, …) that can be mobilized any time. Snow melt or rain could trigger a debris flow any moment, probably not of the size of the event on Sunday, but critical for anybody and anything close to the river. Also on the mid term, the debris flow potential is certainly very much increased now, not only during the next day, but in particular also in view of further snow melt and later heavy monsoon precipitation.

Further it would be important to collect information on the following:

- Analyses of discharge records to constrain timing of processes
- Analyses of meteorological conditions over past weeks (Temperature and Precipitation, snow fall and snow fall limit, snow melt, etc. of the days and weeks prior to the event)
- Any records of nearby seismic stations, in order to better constrain the timing of the avalanche and temporal evolution of subsequent processes.
- Any report, photos, field data etc. would be of great value to improve the understanding of this event and the processes involved.

UPDATES FEBRUARY 20, 2021:

Volume of the rock-ice avalanche

High resolution satellite imagery from various sources indicate a much deeper failure zone than initially estimated, involving roughly 10 times more volume than initially estimated (Figs. U1-1 and U1-2).

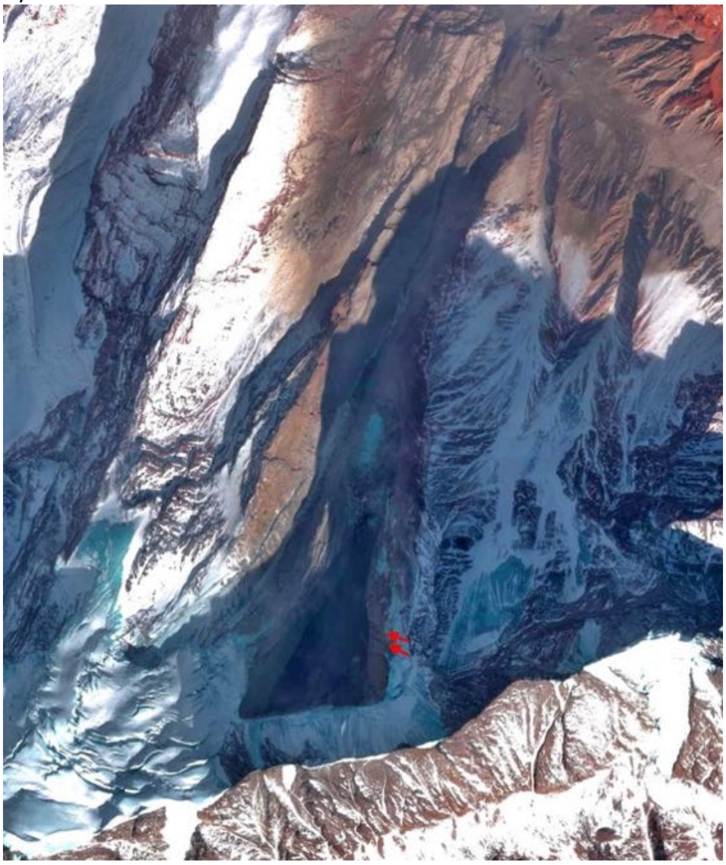

Figure U1-1: Pléiades image from Feb 9 2021. Red arrows indicate presence of liquid water. (Source: Pléiades CNES / Airbus DS. Courtesy of S. Gascoin and E. Berthier)

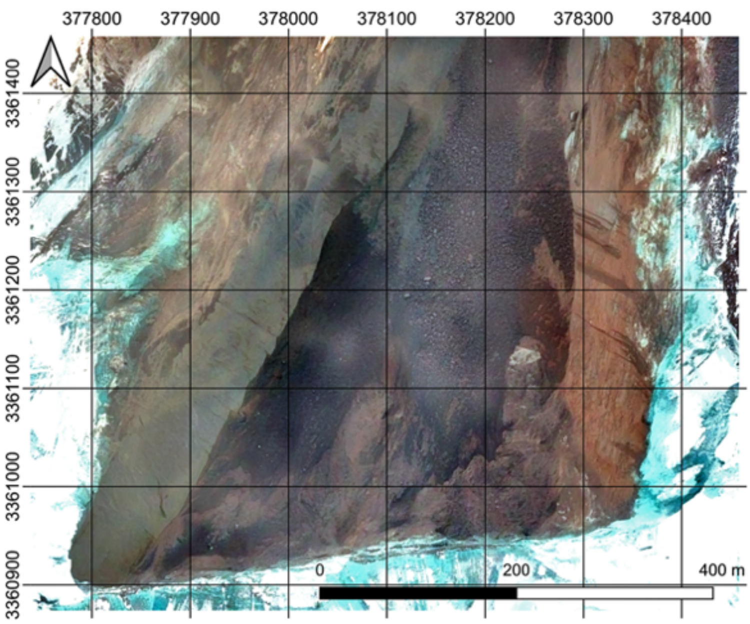

Figure U1-2: Zoom to source zone. (Source: Pléiades CNES / Airbus DS. Courtesy of S. Gascoin and E. Berthier)

Stereo imagery from the Pléiades satellites acquired on February 10 was used to generate a post event Digital Elevation Model (DEM). DEM differencing with different DEMs representing pre-event topography revealed a detached volume of about 25 million m^3 (Fig. U1-3).

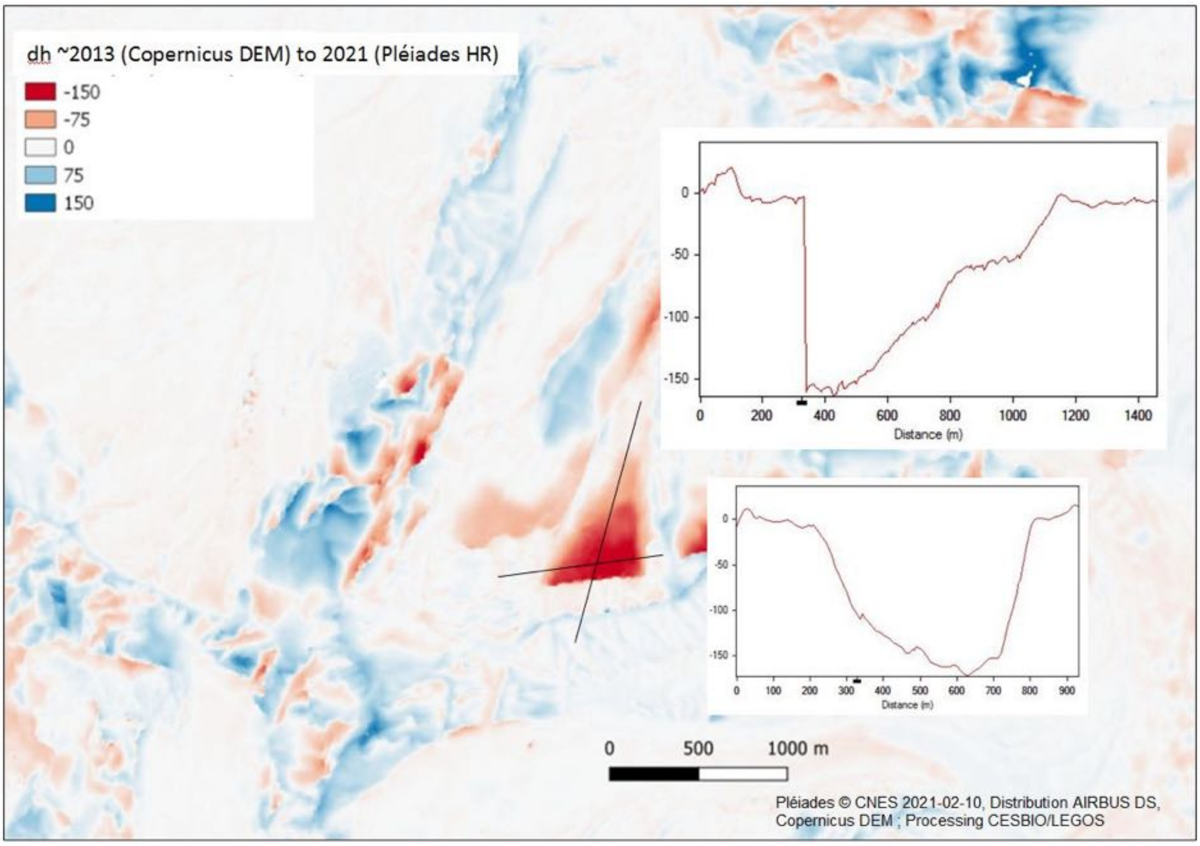

Fig U1-3: Difference of post event topography from new 2021 Pléiades stereo DEM minus pre event topography from 2013 Copernicus DEM. Inserts show elevation difference profiles on two axes (black lines) across the failure zone (upper panel: slope direction, lower panel: cross slope direction. (Source Pléiades and Copernicus, courtesy of E. Berthier).

New estimates of the rock ice composition yield ca. 20 million m^3 of rock (83%) and ca. 4 million m^3 of ice (17%). This is a major change in comparison to the 1-10 million m^3 estimated initially and puts this event into a category of the largest contemporary mass movements in mountains at global scale.

Considering the depth of the failure plane of more than 100 m below surface at the top end of the detachment zone makes it less surprising that this failure occurred in winter. At these depths no seasonal temperature variations are expected. The detachment zone is expected to be in permafrost conditions (ground temperatures perennially below zero). Heat fluxes from the warmer south face of the mountain to the colder north face, where the avalanche detached, could have warmed the frozen bedrock, and therefore might have played a role in the slope failure. Furthermore liquid water from snow and ice melting could have infiltrated the bedrock in cleft systems and destabilized the rock through freeze-thaw processes (post event imagery provides evidence for liquid water in the detachment zone, see red arrows in Fig. U1-1. An important factor in terms of basic disposition is the geologic structure and lithology. Rock layering at the failure zone of Trisul peak is parallel to slope which makes it more prone to failure processes, i.e. represents an unfavorable layering. However, the initiation of the failure (movements can be tracked back in high-res satellite imagery to about 2016) as well as the eventual trigger of the avalanche remain unclear. It is also important to note that unstable geological configuration and steep topography can on its own be a sufficient driver of large slope failures.

Flood

Eyewitness videos from social media are analyzed to reconstruct flow velocities and discharge of the flood, by combining information from the videos with high-resolution satellite imagery (Fig. U1-4). In the area around Raini, about 15km downstream the avalanche source area, flow velocities are estimated about 25 m/sec with a discharge between 8,200 m^3/sec and 14,200 m^3/sec. Around the Tapovan hydropower station, at 23.6 km and 25.7 km from the avalanche source area, flow velocities are estimated about 11.7 m/sec to 16 m/sec, with a discharge between 2,850 m^3/sec and 8,420 m^3/sec.

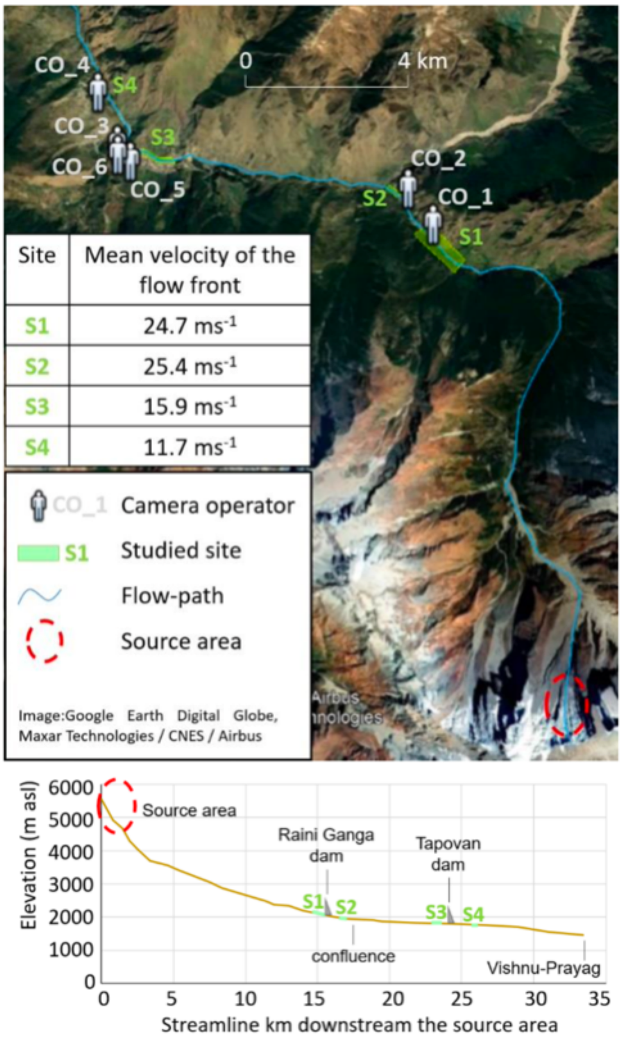

Figure U1-4: Four study sites used to estimate mean flow front velocity and discharge along the flow-path and approximate location of six camera operators. (Courtesy of A. Emmer).

Sources of water

Theoretical considerations of frictional heating within the avalanche, taking into consideration the avalanche composition of around 80% rock and 20% ice and the vertical fall height have been refined. This analysis revealed, that, depending on how large other energy sinks are, 50% or more of the ice could have been melted within the avalanche. In absolute volumes, this could result in more than 2 million m^3 of water.

This frictional heating and melting of avalanche ice was considered as a potential source of water already in the first version of this summary. But new insights on the total volumes involved and the volumetric shares of rock and ice, imply much more favorable conditions to melt large amounts of ice by this process.

In turn it was found that the deposits from the 2016 ice avalanche of the neighboring glacier in the valley below the Feb 2021 avalanche have had disappeared more or less before the recent event (Fig. U1-5). Thus, buried ice deposits have not played a major role as a source of water for the flood, as initially speculated.

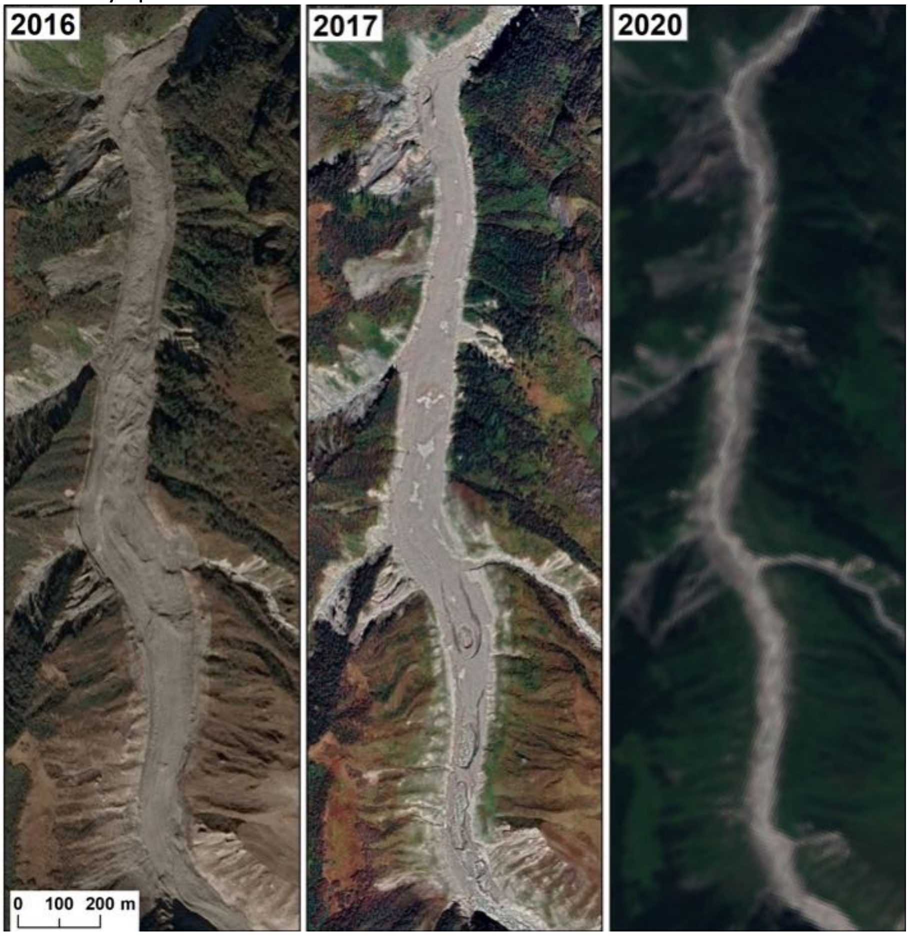

Figure U1-5: Deposits of the 2016 ice avalanche from the neighboring glacier. The 2020 pre event Sentinel-2 image (right panel) indicates normal flow of the river. The debris-covered ice, visible in the left and central panel from 2016 and 2017, seem to have disappeared before the 2021 avalanche. (Courtesy of Mikhail Dokukin).

Nevertheless, water stored in (potentially saturated) sediments could have contributed significant amounts of water to the flood. Other events showed, that such sediments can store considerable amounts of water, which can be mobilized when eroded. News articles mention villagers that have reported an "extremely pungent smell in the air" when the flood was passing (http://timesofindia.indiatimes.com/articleshow/80765995.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst). Such smells had also been reported in other events, where water stored in sediments was mobilized.

New calculations and estimates show, that even if the entire water in the rivers had been incorporated into the hyperconcentrated flow (hyperconcentrated flows typically contain around 20-30% solid material and 70-80% liquid content), this would only have provided a minimal contribution to the flood. Some satellite imagery indicate that the reservoir behind the Raini dam was full, which could be an additional source of water.

At the confluence upstream the Raini village, deposits of the hyperconcentrated flow dammed the tributary valley and a glacial lakes has formed. Social media reports and news articles show that missions on the ground are monitoring the situation and observing this subsequent hazard. The fact that it took about two to three days for this lake to form an reach its current size, indicates, that a temporary lake is a rather unlikely source of water for the main flood event on February 7.

The hypothesis that the avalanche had triggered a subglacial water pocket (a subglacial water body) very unlikely, is according to our insights into this event. Nevertheless, this theory seems to still be prominent in media coverage (e.g., https://www.newindianexpress.com/nation/2021/feb/12/ice-avalanche-subglacial-lake-burst-set-off-flash-floods-scientist-2262886.html). We have no evidence of a flood originating form a glacier tongue in the area.

Another theory, currently mentioned in media articles, is that a rock-ice avalanche after September 2020 blocked the Ronti Gad river, and high air temperatures prior to February 7 led to a failure of this dam, which caused the flood (e.g., https://lifestyle.livemint.com/news/big-story/on-thin-ice-how-climate-change-is-wrecking-the-himalaya-111613732035880.html).
However, we carefully checked high resolution Planet imagery, acquired between September 2020 and February 2021. There are no signs of a major avalanche, dam or dammed lake that would have the size required to play an important role in the February 7, 2021 flood.

Current and subsequent hazards

We emphasize and reiterate our urgent call to establish and maintain a dense network of persons surveying the situation and able to emit alarms for evacuation in case needed. This network has to extend from the avalanche site and along the entire stretch of the river.

Regarding subsequent hazards, we still see four core issues:

1. *Detachment zone*: Probability for following failures and mass movements.

The scar has a vertical back wall of almost 150 m height. The large block of rock above this wall up to the ridge could be unstable. Adjustment of stress fields due to the detached mass imply long term changes of the stability of the remaining rock masses.

High-resolution images (cf. Fig. U1-2) show many large boulders present in the lower part of the avalanche scar. They could be unstable and easily mobilized.

Recent high resolution satellite imagery indicates mass movement activities are ongoing in the source zone where the initial rock and ice failed. In case of another (likely smaller) slope failure and avalanche, this can be critical for people and infrastructure downstream, close to the riverbed. It can be normal follow up activity of the main event, but it cannot be excluded that important secondary events can occur.
Although a second event of this magnitude seems unlikely, it cannot be ruled out. We consider urgent to closely and regularly (if possible daily) monitor the slope failure zone at Trisul Peak to detect signs for a possible second avalanche. We also highly recommend detailed long term monitoring of this situation. Repeat photogrammetric DEMs from UAVs or terrestrial radar scans could help to identify potential movements.

2. *Deposits:* Potential source for debris flows.

Large volumes of material have been eroded and deposited along the river channel. In combination with water from rivers, snow melt, heavy (monsoon) rainfall or overflow of temporary lakes, debris flows can be triggered from these depositions. This needs to be monitored.

3. *Temporary lake:* Potential dam instability.

It is difficult to assess the state of the temporary lake at the confluence above Raini from remote sensing data only. Dam conditions need to be critically analyzed. According to media coverage, authorities on the ground are constantly monitoring and assessing the situation and have the lake under control.

4. *Undercut slopes:* Potential slope instabilities and landslides.

Erosion by the flood probably has undercut some slopes. Some high resolution satellite images indicate tension cracks on and above slopes with signs for movements, but it is difficult to evaluate the evolution of these cracks and attribute them to the February 7 avalanche. Detailed evaluation and monitoring of the slopes along the entire stretch of the river are recommended. Such slope instabilities could affect roads, villages and other infrastructure located far above the river bed.

Data needs

In terms of data needs, we renovate our request from the initial summary.
Under the current situation and state of knowledge, it would be most helpful to get the following information:

- Seismic records from February 6 and 7 from the Joshimath seismic station.
- Runoff information and measurements along the rivers.
- Photos and reports from the missions on the ground.