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The 23rd April '21 Snow Avalanche, Girthi Ganga post the 7th February '21 Rishi Ganga Flash Flood: Are these Events Linked to Climate Warming in the Western Himalaya?

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ABSTRACT

The upper catchment of Dhauli Ganga valley (Chamoli district) in Uttarakhand Himalaya recently witnessed a large snow avalanche on the night of 23rd April 2021 along the Indo-Tibet border. This event followed the 7th February 2021 Rishi Ganga (debris flow induced) flash flood within less than three months. This note analyses the plausible causes of the avalanche using pre-disaster field survey data, supported by the limited geological and remote sensing based geomorphological investigations as the site could not be investigated due to remoteness of the location and travel restrictions due to COVID pandemic. The present observations suggest that active and relict cirques to the north of the South Tibetan Detachment System (STDS) are the sites for potential snow and debris avalanches under the projected warming trends in the western Himalaya. Particularly, the study calls for climate change adaptation measures in the climate sensitive Trans Himalayan region and optimize anthropogenic activities in order to safeguard the lives and vital infrastructure.

INTRODUCTION

The recent 7th February 2021 Rishi Ganga (debris-flow) flash flood, and the large snow avalanche of 23rd April 2021 in the Girthi Ganga valley near the Indo- Tibet border occurred in the upper Dhauli Ganga catchment (>3500 m asl). The steep terrain, seismicity, fragile geological formation, and intense and highly variable precipitation trends, make the region vulnerable to floods, landslides, avalanches, and, debris flows (Rawat et al., 2012; Vaidya et al., 2019). Geomorphologically, the valleys at higher elevations (>2500 m asl) are dominated by paraglacial processes that are directly conditioned by the modern glaciers and are constantly adjusting to changing glacier boundary conditions due to local and regional climate variability (Church and Ryder 1972). These valleys also sequester paraglacial debris left behind by the receding glaciers (Ali and Juyal, 2013) which can be mobilized by short-lived extreme weather event (Sundriyal et al., 2015). Thus, the paraglacial zones are not only ecologically fragile but are geomorphologically unstable due to constant re-sedimentation and transfer of glacial sediments (Barnard et al., 2004).

The vulnerability of the terrain is well appreciated for the extreme events such as flash floods, which are likely to increase in frequency by 10% and over 30% of the existing magnitudes in Uttarakhand Himalaya (UAPCC, 2014). Various studies indicate that the Himalayan region has also witnessed significant warming in the recent decades particularly at the higher elevation (Krishnan et al., 2019). For example, the warming trend over 2000 m asl during the early twentieth century was about 0.10 °C per decade, which later doubled to 0.32 °C per decade (Yan and Liu 2014). A more recent study by Sabin et al., (2020) suggested that the warming was more amplified over 4000 m asl (0.5 °C/decade). Also, in most parts of the Himalayan region, warming rate is reported to be more substantial in winter as compared to other seasons (Bhutiyani et al. 2007). The rising temperature directly influences the melting of glaciers, snow, and permafrost to generate cascading effects (Mool et al, 2011; Bolch et al., 2012; Wang et al., 2019). For example, degrading high-mountain permafrost increases the probability of rock ice/avalanches from steep slopes reaching glacial lakes and triggering Glacial Lake Outburst Floods (GLOFs) (Haeberli et al. 2016). Such hazards have severe implication for the people, and existing infrastructure, such as dams, bridges and roads.

The 23rd April 2021 Girthi Ganga snow avalanche destroyed the Border Road Organization's (BRO) temporary shelter camp for the labourers who were engaged in the strategically important Indo-Tibet border road construction. Available reports indicate that the avalanche claimed sixteen lives while 384 people were rescued. Considering the sensitivity of the Trans Himalayan terrain to snow avalanches, the study (i) analyses the plausible causes of the avalanche and (ii) explores the potential geomorphic features that most likely make the terrain vulnerable to such events under the projected climate trends. The geological and geomorphological investigations undertaken during pre-disaster field survey (2018) supported by the available aerial photograph, video and Google Earth imagery was used. Due to remoteness of the location and travel restrictions due to COVID pandemic, the site could not be visited after disaster.

STUDY AREA

The 23rd April 2021 avalanche occurred in the upstream of Malari village in the Girthi Ganga valley- a tributary of the Dhauli Ganga in the upper Alaknanda catchment. Geologically, the semi-arid/arid terrain lies in the rain shadow zone of the Higher Himalaya (Nanda Devi Massif; a World Heritage Site) (Fig.1). The Indian Summer Monsoon (ISM) is the major contributor of moisture during summer, while the subordinate contribution comes from the westerly disturbances during the winter months (Bisht et al., 2015). The Girthi Ganga river originates from Jandi Dhura (5900 m asl) - a cirque glacier and flows westward to meet Dhauli Ganga river near the Malari village. Observations from Google Earth imagery of the Dhauli Ganga watershed show that there are several relict and a few active cirques with steep slope profiles that are directly coupled with the Girthi and Dhauli Ganga river valleys (Fig.1). Presently, the Girthi Ganga valley slopes are barren and devoid of any large valley glaciers. The Dhauli Ganga valley however, has a few big glaciers (>5 km) such as Dunagiri, Kosa, Bagini, Bankund, Semkharak and Purvi Kamet (Fig.1). The bigger valley

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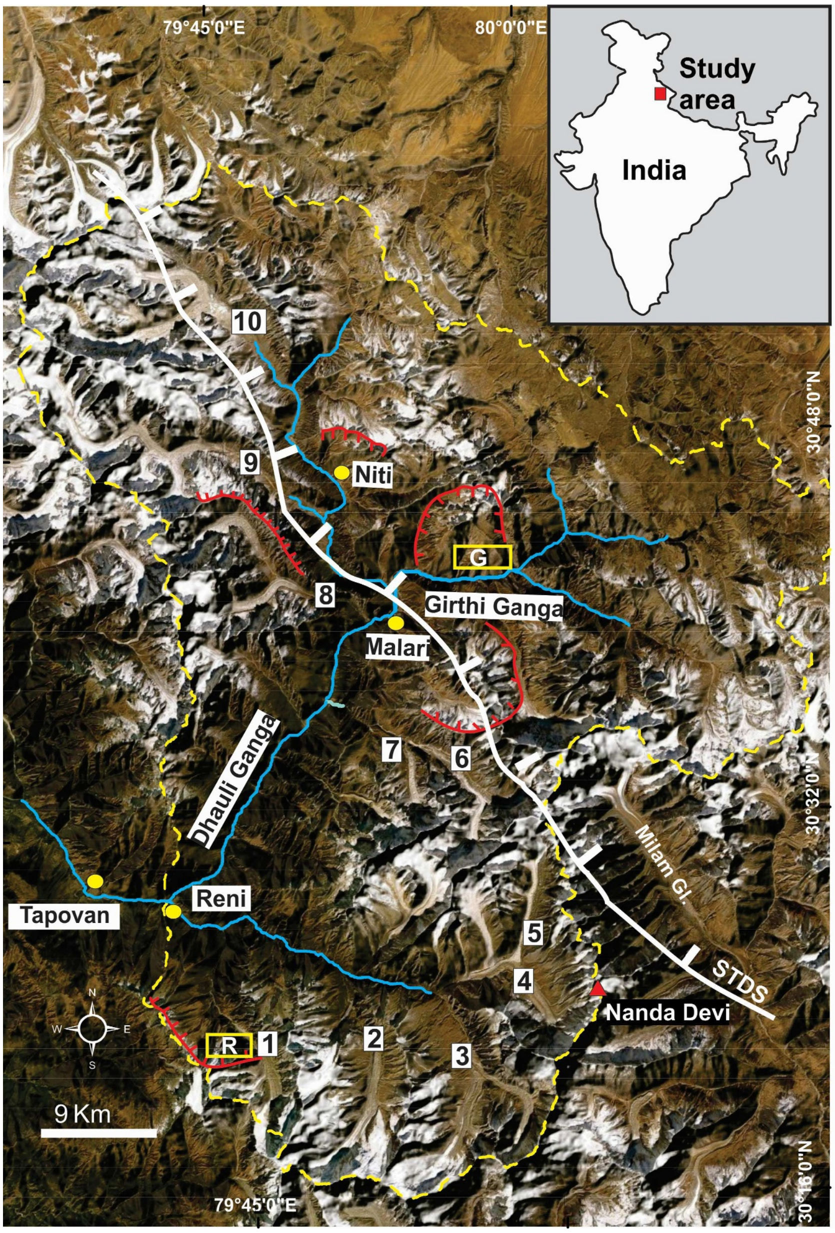

Fig.1. The GeoEye satellite imagery (ESRI base map) showing catchment of Dhauli Ganga (yellow dashed line). The ridgelines of active/relict cirques (red lines) are potential locations of generating avalanche prone debris flows in the catchment. Red triangle marks the location of Nanda Devi peak (7816 m asl); major glaciers are numbered from 1 to 10. 1-Raunti glacier (Gl.), (2-Trishul Gl., 3-S. Rishi Gl., 4-S. Nanda Devi Gl., 5-N. Nanda Devi Gl., 6-Bagni Gl., 7-Dunagiri Gl., 8-Kosa Gl., 9-Bankund Gl., 10-Purvi Kamet Gl. Approximate position of STDS-South Tibetan Detachment System demarcate the Higher Himalaya from the Trans Himalaya. The locations of 7th Feb 2021 (Yellow rectangle with R) and 23rd April 2021 (yellow rectangle with G) disasters are marked. Both the events highlight the potential of seemingly insignificant valleys to generate disasters, and hence sensitivity of the terrain to possible natural/anthropogenic triggers.

glaciers are relatively stable due to graded longitudinal profiles, unless there is a major structural failure as observed in Raunti gad (stream) on 7th February 2021 (Rana et at., 2021) (Fig.1).

RESULT AND DISCUSSION

7th February Flash Flood and 23rd April Avalanche

On 7th February 2021, a massive rock and ice fall was triggered by the failure of a pre-existing fissure in Raunthi gad (in a small tributary glacier) that is believed to be facilitated by melting of the fresh snowfall as the temperature warmed (Rana et al., 2021). The amalgamated mass of snow and rock most likely caused temporary impounding of the constricted channel downstream. This temporary (short lived) dam would have busted to generate the pulse of flood. Additionally, the debris flow could have incorporated the englacial meltwater associated with the dead ice cavities in the paraglacial sediments, and also from thawing permafrost (ICIMOD 2021; Pandey et al., 2021; Rana et al., 2021; Sain et al., 2021).

In comparison, the 23rd April 2021 event was a snow avalanche that occurred in the catchment of south-facing relict cirques having steep slopes. The relict/active cirques are bowl shaped depressions (Fig.2) with steep headwalls which have been carved out by former glaciers. Many of these cirques are complex type with several smaller valleys inset (up to 0.1 km^2) within their ridge line. Studies indicate that in the geological past the terrain was extensively glacierized with multiple cycles of glacier expansion and recession. The last minor advance is suggested to occur during the Little Ice Age (~500 yr ago) (Sati et al., 2014; Bisht et al., 2015). The available aerial images and a video of the 23rd April event show a well-formed track with a deposit at the bottom of the runout zone (Fig.2; Source: Reuters and BRO). In absence of the satellite images for the day of avalanche, the present analyses based on geomorphology indicate that the avalanche might have been initiated at the crown of the relict cirque. The south facing slopes are known to generate hazardous, large, wet snow avalanches because the increase in temperature lead to the decrease in snow pack stability (Ancey, 1999). The smaller, steep sloped, depressions collect seasonal snow which builds up, and is then suddenly rolled down slope under the influence of gravity (Podolskiy et al. 2010). The steeper the slope, shorter is the critical length required for snow slab failure (Schweizer, 1999) which seems to be the case for the Girthi Ganga avalanche. It has been suggested by previous workers that weak snow layer is one of the major factors responsible for initiating the sudden snow avalanches in such terrains (Schweizer, 1999), especially during favourable meteorological conditions/trigger (Ancey, 2001).

The spatial distribution of avalanches is suggested to be highly localized where other well established/known factors which may have been responsible for trigging snow avalanches include: terrain characteristics (slope, aspect, altitude, and inclination), meteorological conditions (temperature, precipitation, wind, thickness of snow layer) and snow pack conditions (characteristics of snow grain) in addition to vegetation (Luckman, 1977; Podolskiy et al. 2009). Local meteorology strongly influences snow properties such as granular size, cohesion, shear strength, and snow pack layer stratigraphy which are known to be critical for avalanches (Bartelt and McArdell, 2009; Schweizer et al., 2021). Considering the above, it is most likely that the 23rd April avalanche was the result of site-specific combination of multiple factors.

The Trans-Himalaya is vulnerable both in terms of its geological and structural settings as well as the changes in temperature and precipitation trends. For example, the Girthi Ganga valley is located on the hanging wall of the South Tibetan Detachment System (STDS). The STDS is a coupled structure with the tectonically active Main

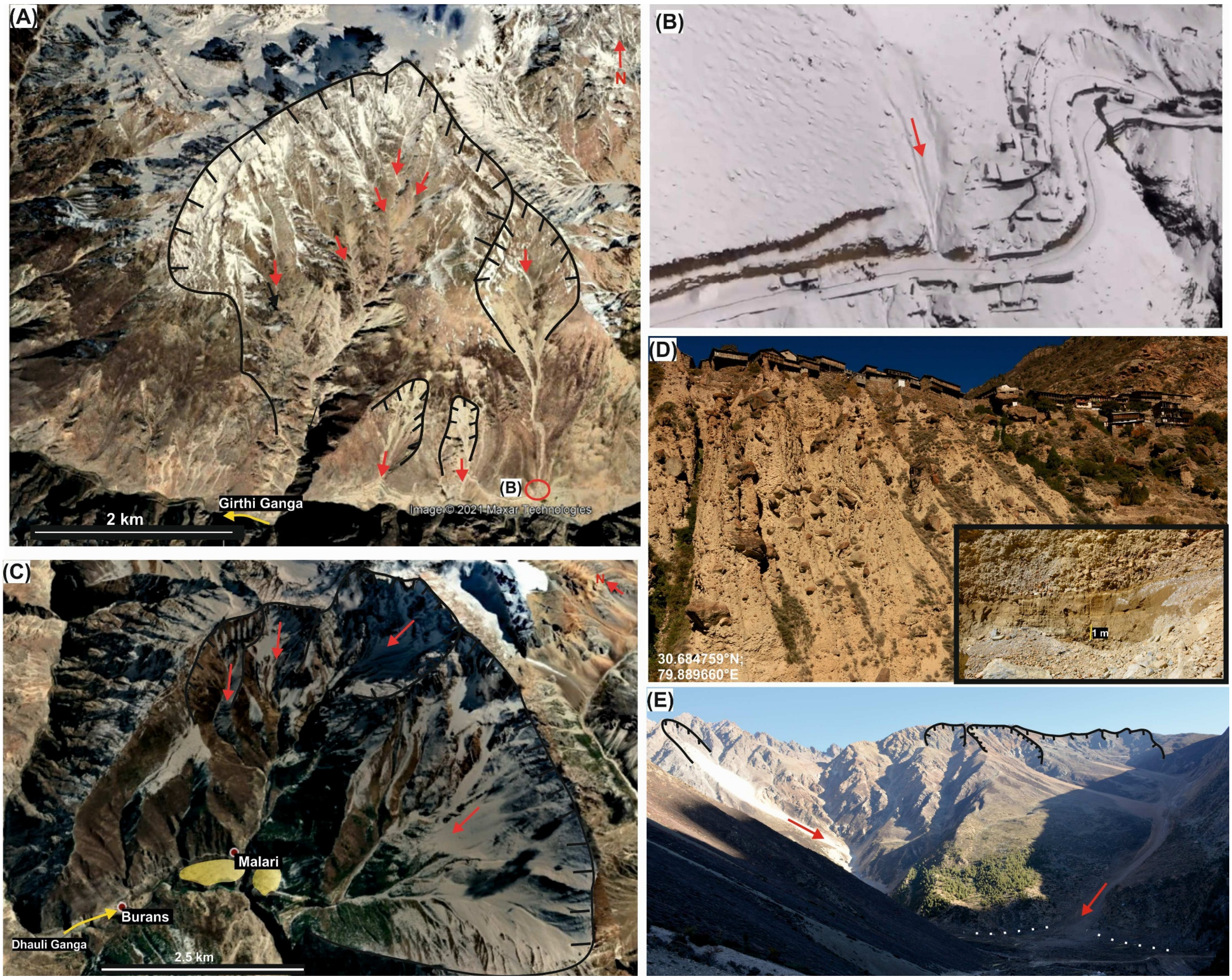

Fig.2. **(A)** Google Earth imagery showing relict cirques (bowl-shaped depressions) where sharp breaks/steeper segments promote breaking of snow slab after heavy snowfall. Red circle marks the disaster site of 23rd April 2021. **(B)** The photograph of avalanche track that happened at the night on 23rd April 2021 (courtesy: Border Road Organization). **(C)** Google Earth imagery of Malari village showing relict/active cirques which may be potential sites of avalanche generated debris flows. Yellow colour marks the location of relict debris flow deposit over which the village is located. **(D)** Field photograph (dated Oct-2018) of debris flow deposits at Malari village indicating that the valleys have witnessed extreme weather events with likely contribution from avalanches in the past with close-up of sedimentary texture (inset). The sedimentary texture shows crude upward fining with dominance of granular matrix mixed with fine silty-sand and presence of angular clast. **(E)** Field photograph of active/relict cirque glaciers opposite Niti village. Such cirques are potential sites for avalanche generation. The source (cirque), track (red arrow) and debris deposit (white dotted lines) of one possible historical avalanche is marked.

Central Thrust (MCT) and is known to be tectonically active during the Holocene (Rana et al., 2013). Most likely the STDS is also providing accommodation space for compressive strain during the recent times (Hurtado et al., 2001). Hence, the role of micro-seismicity as one of the triggering mechanisms cannot be ignored in generating avalanches in this region and would require analysis of seismic data from the region. Excavation activities and use of explosives during road and infrastructure construction may also make the slopes unstable that could cause localized near surface loading and trigger avalanche. Needless to say, further analysis is needed to assess the role of these factors.

Are these Unusual Events Linked to Climate Warming?

The 7th February 2021 Rishi Ganga flash flood, the 23rd April 2021 Girthi Ganga snow avalanche, 27th April 2021 avalanche in Siachen (Karakoram), the 4th May 2021 cloudbursts in Chamoli, Almora, Tehri, Rudraparyag (Uttarakhand) and in Chamba (Himachal Pradesh) indicate that possibly the triggering factor is regional. It may be the predicted response of the terrain to the increased frequency of multiple geomorphic hazards -debris flow, flash flood, avalanche to rising temperatures over Western Himalaya (IPCC, 2014). The terrain experienced spells of snowfall in the April month with heavy snowfall during past few days prior to the avalanche. This could have led to sudden loading and therefore might have triggered the 23rd April 2021 avalanche. Most of the avalanches in Himalaya are known to be triggered between January-March (Ballesteros-Cánovas et al., 2018), where powder snow avalanches tend to occur due to cumulative snow precipitation. Given the unusual timing of the avalanche (spring) it is speculated that warmer snow surface temperature (0°C) with rising insolation could have additionally produced wet and dense flow, where the presence of liquid would have deformed the snowpack to release the avalanche (Baggi and Schweizer, 2009; Ancey and Bain, 2015).

A recent study based on tree rings by Ballesteros-Cánovas et al.,

(2018) has demonstrated a correlation between the early winter/spring warming and increasing incidences of wet snow avalanches in the Himalaya. The findings are at variance with the conventional wisdom that warming results in less snow, and thus, lower avalanche activity. Recently released Ministry of Earth Science (MoES) report (Sabin and Krishnan 2020), mentioned that the Himalayas and the Tibetan plateau have experienced substantial warming during the twentieth century, where the warming trend has been particularly pronounced over the Hindu Kush Himalaya (HKH). The study observed an increase in the annual mean surface-air-temperature of around 0.2 °C per decade (1951–2014) for which anthropogenic induced climate change is implicated. However, what is alarming is that above 4 km the rise in air temperature is found to be > 0.5 °C per decade (Sabin and Krishnan, 2020). Further, there is an indication that the warming is more substantial during winter season (Bhutiyani et al. 2007; Shrestha et al., 2010), particularly the northwestern Himalaya witnessed warmer and wetter winter with decreasing trend in snowfall during the last 25 years (Negi et al., 2018). Thus, one is tempted to attribute the recent Chamoli events to the ongoing human-induced warming. However, a definite inference towards the cause of recent disasters in the region should await rigorous analyses of local and regional meteorological data supported by intensive field study in the Trams Himalayan region.

CONCLUSIONS

The snow avalanches on steep mountain slopes may accompany rock falls and are often mixed with debris (Schweizer et al., 2021) as seen in 7th February event. In addition to the meteorology, which is a very important input parameter for forecasting (SASE, 2018), a more detailed terrain analysis incorporating geological archives can help to identify avalanche-prone areas; thus, prioritizing sites for future monitoring. For example, the slopes between 25° and 50° are shown to be most susceptible in the bowl-shaped catchments having narrow tracks where avalanches may be triggered by high snow water equivalent and high snowfall loading (Snehmani et al., 2014). The cirques in the Dhauli Ganga catchment (including the site of 23rd April avalanche), have prominent barren channels with levee like structures indicating track marks of historical channeled avalanches with remnant of debris cones near the valley bottom (Fig.2E). Such locations may help in generation of geological history of these events and therefore enhance our understanding and prediction capabilities.

Disasters are red-flagging events indicating the vulnerability of the higher Himalayan valleys (particularly glacial and paraglacial zones). Given the alarming impact of climate change scenario, it requires careful monitoring and scientific analysis pertaining to the frequency and magnitude of paraglacial zone hazards (Negi et al., 2018; Ballesteros-Cánovas et al., 2018; Sabin and Krishnan, 2020). The incidences reinforce our concern that high altitude regions in the Himalaya require climate change adaptation strategies in order to safeguard the vital infrastructure development activities (Rana et al., 2021). Given the numerous vulnerable valleys and multiple triggering factors, predicting the extreme weather events and protecting the people/infrastructure from their impact is a challenging task. Incorporating the geomorphological and geological scientific understanding may help us to focus our resources in the right direction to reduce the vulnerability and minimize the human suffering and economic loss.

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