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Debris cover growth, ensuing changes in morphology and impact on glacier processes at Pensilungpa Glacier, western Himalaya, India

Purushottam Kumar Garg¹, Aparna Shukla^{2,3}, Vinit Kumar³, and Manish Mehta³

¹Centre for Glaciology, Wadia Institute of Himalayan Geology, Dehradun-248001, India (garg.glacio@gmail.com)

²Ministry of Earth Sciences, New Delhi-110003, India

³Wadia Institute of Himalayan Geology, Dehradun-248001, India

Supraglacial debris affects the melting processes and overall response of glaciers to climate change. The present study investigates the temporal variation in debris cover and its influence on the overall state of the Pensilungpa glacier ($14.67 \pm 0.29 \text{ km}^2$), western Himalaya, India, which has extensive debris on its lower ablation zone (LAZ). For this, multiple parameters namely length, area, debris extent/thickness, snowline altitude (SLA), surface ice velocity (SIV), surface elevation changes and ice-cliffs were determined using field measurements (2016-2018), GoogleEarth images (2013-2017) and satellite data (Landsat-TM/ETM+/OLI (1993-2017), SRTM (2000) and Terra-ASTER (2017)) to comprehend the past and present status of the glacier. Results show a moderate terminus retreat ($6.62 \pm 2.11 \text{ m/y}$) and area loss ($0.11 \pm 0.03\%/y$) but a marked slowdown ($\sim 50\%$) in the glacier supported by significant SLA upshift ($\sim 6 \text{ m/y}$) during 1993-2017. Geodetic measurements reveal a prominent downwasting of $-0.88 \pm 0.04 \text{ m/y}$ during 2000-2017 which is corroborated with ablation-stake measurements that show average annual melting of -0.88 m during 2016-2017 and -1.54 m during 2017-2018. The glacier moved with a slow velocity of $13.94 \pm 3.94 \text{ m/y}$ in 1993/94 and its velocity further slowed-down to $9.33 \pm 2.76 \text{ m/y}$ in 1999/2000 and to $7.63 \pm 3.87 \text{ m/y}$ in 2016/17 revealing a slow-down of $1.97\%/y$. Notably, the magnitude of change in most glacier parameters was lower in the recent period (2000-2017) as compared to the previous one (1993-2000). The observed SLA upshift (180 m), area loss ($0.17 \pm 0.24\%/y$) and slowdown rates ($4.73\%/y$) were much higher during 1993-2000. Contrarily, the glacier experienced a low area loss ($0.09 \pm 0.09\%/y$), slowdown ($1.14\%/y$) and even descend in SLA (43 m) between 2000 and 2017. The overall glacier depletion has resulted in substantial debris cover increase of $2.86 \pm 0.29\%/y$ during the study period (1993-2017). Following the glacier depletion trend, the debris growth rate was also much higher ($6.67 \pm 0.41\%/y$) during 1993-2000 and reduced (to $0.81 \pm 0.12\%/y$) subsequently (2000-2017). The most recent estimate (2016) shows a total debris cover of 17.35% on the Pensilungpa glacier and field measurements show that the debris tends to be thicker towards the margins. Such a setting probably insulated the glacier margins which, coupled with steady slowdown, has caused the stagnation of the LAZ up to 2 km upstream, which is reflected in SIV results and temporal GoogleEarth images. Also, the debris thickness distribution on glacier is such that it is thicker near the snout ($>40 \text{ cm}$) and gradually decreases upstream ($<2 \text{ cm}$ at $\sim 2.5 \text{ km}$). This has caused differential melting by insulating-effect and albedo lowering-effect and has promoted slope inversion, contributing further to stagnation. Stagnation of the LAZ has caused

bulging in the dynamically active upper ablation zone and favored the development of supraglacial lakes (5 in 2017) and numerous ice-cliffs (79 in 2017). In view of insulated margins, back-wasting of ice-cliffs dominates the ablation process which is evident by rapid expansion in their number (48%), perimeter (31%) and area (41%) during 2013-2017. To conclude, the debris cover has significantly altered multiple glacier processes and has largely controlled the glacier evolution.