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Scientific Editor: [*Journal of Glaciology*](#), International Glaciological Society

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Outstanding Reviewer Award [*Remote Sensing of Environment*](#) 2018

Project referee (6): *Science & Engineering Research Board (SERB), a statutory body under the Department of Science, Government of India.*

Himalayan Cryospheric Observations and Modelling (HiCOM) initiative by National Centre for Antarctic and Ocean Research (NCAOR), Ministry of Earth Sciences (MoES).

Project (1): Mega project (₹ Thirty two lakh) ‘Damage Assessment Mapping of Bhagirathi River Valley with special reference to an extreme rainfall event of the June 2013’, Co-investigator, Funding Agency - Ministry of Science and Technology, Indian Government. Duration 12 months, Status – Completed.

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- Attended four weeks ‘**Field Training Course in Glaciology**’ organized by Geological Survey of India at Hamtah Glacier, Himachal Pradesh from 07/08/2012 to 03/09/2012.
- Attended one-week basic training course on ‘**Himalayan Glaciology**’ organized by Wadia Institute of Himalayan Geology from 06/09/2010 to 15/09/2010.
- Attended two weeks special course on "**Performance Evaluation of Canal Irrigation Projects using Remote Sensing and GIS**" organized by Indian Institute of Remote Sensing (IIRS), Dehradun from 15/04/2010 to 24/04/2010.
- Attended one week GIS training program on ‘**Introduction to ArcGIS 9**’ organized by ESRI India, New Delhi from 11/10/2004 to 15/10/2004.

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Since 2014: Himalayan Geology Society – HGS – www.himgeology.com/himgeol/himalayan.htm

PUBLICATIONS

PEER-REVIEWED JOURNALS

- [23] King O, Bhattacharya A, [Bhambri R](#), and Bolch T (2019) Glacial lakes exacerbate Himalayan glacier mass loss. *Scientific Reports*, 9(1), pp.1-9.
- [22] [Bhambri R](#), Hewitt K, Kawishwar P, Kumar A, Verma A, Snehmuni, Tiwari S, Misra A (2019) Ice-dams, outburst floods, and movement heterogeneity of glaciers, Karakoram. *Global and Planetary Change* 180, 100-116.
- [21] Kumar A, [Bhambri R*](#), Tiwari S K, Verma A, Gupta A K, and Kawishwar P (2019) Evolution of debris flow and moraine failure in the Gangotri Glacier region, Garhwal Himalaya: Hydro-geomorphological aspects. *Geomorphology*. 333, 152-166.
- [20] Kumar A, Gupta A K, [Bhambri R](#), Verma, A, Tiwari S K, and Asthana, A K L (2018) Assessment and review of hydrometeorological aspects for cloudburst and flash flood events in the third pole region (Indian Himalaya). *Polar Science* 18, 5-20.
- [19] Kumar A, Verma A, Gokhale A A, [Bhambri R](#), Misra A, Sundriyal S, Dobhal D P and Kishore N, (2018) Hydrometeorological assessments and suspended sediment delivery from a central Himalayan glacier in the upper Ganga basin. *International Journal of Sediment Research* 33(4), 493-509.

- [18] Verma A, Kumar A, Gupta A K, Tiwari S K, [Bhambri R](#), Naithani S (2018) Hydroclimatic significance of stable isotopes in precipitation from glaciers of Garhwal Himalaya, Upper Ganga Basin (UGB), India. *Hydrological Processes* 32,1874-1893.
- [17] Tiwari S K, Kumar A, Gupta A K, Verma A, [Bhambri R](#), Sundriyal S, and Yadav J (2018) Hydrochemistry of meltwater from Dokriani Glacier during early and draining late ablation season, West Central Himalaya. *Himalayan Geology* 39(1) pp. 121-132.
- [16] [Bhambri R](#), Mishra A, Kumar A, Gupta A K, Verma A and Tiwari S K (2018) Glacier Lake inventory of Himachal Pradesh. *Himalayan Geology* 39(1) pp.1-32.
- [15] [Bhambri R](#), Hewitt, K., Kawishwar, P. and Pratap, B., (2017). Surge-type and surge-modified glaciers in the Karakoram. *Scientific Reports*, 7(1), 15391
- [14] [Bhambri R](#), Mehta M, Singh S, Jayangondaperumal R, Gupta A K and Srivastava P (2017): Landslide inventory and damage assessment in the Bhagirathi Valley, Uttarakhand, during June 2013 flood. *Himalayan Geology*, 38(2), pp.193-224.
- [13] Chand P, Sharma M C, [Bhambri R](#), Sangewar C V and Juyal, N (2017): Reconstructing the pattern of the Bara Shigri Glacier fluctuation since the end of the Little Ice Age, Chandra valley, north-western Himalaya. *Progress in Physical Geography*, 41(5), pp.643-675.
- [12] Mehta M, Shukla T, [Bhambri R](#), Gupta A K and Dobhal D P (2017): Terrain changes, caused by the 15–17 June 2013 heavy rainfall in the Garhwal Himalaya, India: A case study of Alaknanda and Mandakini basins. *Geomorphology*, 284, pp.53-71.
- [11] [Bhambri R](#), Mehta M, Dobhal D P, Gupta A K, Pratap B, Kesarwani K and Verma A (2016): Devastation in the Kedarnath (Mandakini) Valley, Garhwal Himalaya during 16th-17th June, 2013: A remote sensing and ground based assessment. *Natural Hazards*. Volume 80, Issue 3, pp 1801-1822.
- [10] Pratap B, Dobhal D P, [Bhambri R](#) and Mehta M (2015): Four Decades of Glacier Mass balance Observations in Indian Himalaya: A Review. *Regional Environmental Change*. 1-16.
- [9] Pratap B, Dobhal D P, Mehta M and [Bhambri R](#) (2015): Influence of debris cover and altitude on glacier surface melting: A case study on Dokriani Glacier, Central Himalaya, India. *Annals of Glaciology*, 56(70), 9-16.
- [8] Paul F, Bolch T, Kääb A, Nagler T, Nuth C, Scharrer K, Shepherd A, Strozzi T, Ticconi F, [Bhambri R](#), Berthier E, Bevan S, Gourmelen N, Heid T, Jeong S, Kunz M, Lauknes T R, Luckman A, Merryman J, Moholdt G, Muir A, Neelmeijer J, Rankl M, VanLooy J and Van Niel T (2015): The Glaciers Climate Change Initiative: Methods for creating glacier area, elevation change and velocity products. *Remote Sensing of Environment*, 162(1), 408–426. DOI: 10.1016/j.rse.2013.07.043.
- [7] [Bhambri R](#), Bolch T, Kawishwar P, Dobhal D P, Srivastava D and Pratap B (2013): Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. *The Cryosphere*, 7, 1385-1398, doi:10.5194/tc-7-1385-2013.
- [6] Srivastava P, [Bhambri R*](#), Kawishwar P and Dobhal D P (2013): Water level changes of high altitude lakes in Himalaya-Karakoram from ICESat altimetry. *Earth System Science*, 122 (6), 1533–1543.
- [5] Pratap B, Dobhal D P, [Bhambri R](#) and Mehta M (2013): Near-surface temperature lapse rate in Dokriani Glacier catchment, Garhwal Himalaya, India. *Himalayan Geology*, 34 (2), 183-186.

- [4] [Bhambri R](#), Bolch T and Chaujar R K (2012): Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965-2006, measured through high resolution remote sensing data. *Current Science*, 102 (3), 489-494.
- [3] [Bhambri R](#), Bolch T, Chaujar R K and Kulshreshtha S C (2011): Glacier changes in the Garhwal Himalayas, India 1968 - 2006 based on remote sensing. *Journal of Glaciology*, 57 (203), 543-556.
- [2] [Bhambri R](#), Bolch T and Chaujar R K (2011): Mapping of Debris-covered Glaciers in the Garhwal Himalayas using ASTER DEMs and Thermal Data. *International Journal of Remote Sensing*, 32 (23), 8095-8119.
- [1] [Bhambri R](#) and Bolch T (2009): Glacier Mapping: A Review with Special Reference to the Indian Himalayas. *Progress in Physical Geography*, 33 (5), 672-704.

BOOKS

[Bhambri R](#), Mehta M, Dobhal D P, and Gupta A K (2015): Glacier lake inventory of Uttarakhand. Special Publication of Himalayan Geology. PP-78.

BOOK CHAPTERS

- Mehta M, [Bhambri R](#), Perumal J, Srivastava P and Gupta A K (2018): Uttarakhand Calamity: A Climate Revelation in the Bhagirathi River Valley Uttarakhand, India. In Disaster Risk Governance in India and Cross Cutting Issues (pp. 193-207). Springer, Singapore.
- Racoviteanu A, Arnaud Y, Baghuna I M, Bajracharya S, Berthier E, [Bhambri R](#), Bolch T, Byrne M, Chaujar R K, Kääb A, Kamp U, Kargel J, Kulkarni A V, Leonard G, Mool P, Frauenfelder R and Sossna I (2014): Himalayan glaciers, in: Global Land and Ice Monitoring from Space: Satellite Multispectral Imaging of Glaciers, edited by: Kargel, J. S., Bishop, M. P., Kääb, A., and Raup, B. H., Praxis Springer, 549–582, doi:10.1007/978-3-540-79818-7, 2014.
- [Bhambri R](#) and Chaujar R K (2009) Recession of Gangotri glacier (1962-2006) measured through Remote Sensing Data. Proceedings of National Seminar on Management Strategies for the Indian Himalaya: Development and Conservation, 1, 254-264.

OTHER JOURNALS

- [Bhambri R](#), Chaujar R K and Kulshreshtha S C (2011): Automated Mapping of Debris-covered Glaciers in the Garhwal Himalayas using Remote Sensing. XXXI Inca International Congress, Indian National Cartographic Association, October 15-17, 2011.
- Kesarwani K, Pratap B, [Bhambri R](#), Mehta M, Kumar A, Karakoti I, Verma A & Dobhal D P (2012): Meteorological observations at Chorabari and Dokriani glaciers, Garhwal Himalaya, India. *Journal of Indian Geological Congress* 4 (1), 125-128.
- [Bhambri R](#), Bolch T and Chaujar R K (2010): Glacier Mapping in Indian Himalaya since the 19th century. *The Himalayan Journal* 66, 173-182.

TECHNICAL REPORTS

Arendt A, Bolch, T, Cogley J G, Gardner A, Hagen J O, Hock R, Kaser G, Pfeffer W T, Moholdt G, Paul F, Radic V, Andreassen L, Bajracharya S, Beedle M, Berthier E, [Bhambri R](#), Bliss A, Brown I, Burgess E, Burgess D, Cawkwell F, Chinn T, Copland L, Davies B, de Angelis H, Dolgova E, Filbert K, Forester R, Fountain A, Frey H, Giffen B, Glasser N, Gurney S, Hagg W, Hall D,

Haritashya U K, Hartmann G, Helm C, Herreid S, Howat I, Kapustin G, Khromova T, Kienholz C, Koenig M, Kohler J, Kriegel D, Kutuzov S, Lavrentiev I, LeBris R, Lund J, Manley W, Mayer C, Miles E, Li X, Menounos B, Mercer A, Moelg N, Mool P, Nosenko G, Negrete A, Nuth C, Pettersson R, Racoviteanu A, Ranzi R, Rastner P, Rau F, Rich J, Rott H, Schneider C, Seliverstov Y, Sharp M, Sigurdsson O, Stokes C, Wheate R, Winsvold S, Wolken G, Wyatt F and Zheltykhina N: Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 3.2. Global Land Ice Measurements from Space, Boulder Colorado, USA. Digital Media.

Sethi M, Khurana ML, [Bhambri R](#), Bundela DS, Gupta SK, Ram S, Chaudhari SK and Sharma DK (2012): Appraisal Of Salt Affected Waterlogged Soils In Rohtak, Bhiwani, Jind And Jhajjar Districts Of Haryana Using Remote Sensing and GIS. Technical Bulletin : CSSRI/Karnal/Bulletin/2012/02 Central Soil Salinity Research Institute; Karnal (Haryana).

IN REVIEW

Misra A, Kumar A, [Bhambri R](#), Haritashya U K, Verma A, Gupta A K, Dobhal D P, Gupta G. and Upadhyay R. (*In Review; Journal of Hydrology*): Topographic and climatic influence on seasonal snow covers over Chorabari Glacier, Garhwal Himalaya, India.

[Bhambri R](#), Watson C S, Hewitt K, Haritashya U, Kargel J S, Shahi A P, Sharma P, Kumar A, Verma A, and Govil H (*In Review; Scientific Report*): The hazardous 2017-2019 surge and river damming by Shispare Glacier, Karakoram.

SUPERVISED MASTER THESES

1. Assessment of Surge Glacier Dynamics on Fisher and Klutan glaciers, St. Elias Mountains, North America. Mr. Arjun Pratap Shahi, Master of Technology in Remote Sensing, Department of Remote Sensing, Birla Institute of Technology, Mesra, 2019.
2. Surface movement estimation of Antarctic Glaciers using Remote Sensing and GIS. Mr. Bidyutjyoti Baruah, M.Sc. in Remote Sensing and GIS, S.S.J Campus, Almora, Kumaun University, Uttarakhand, 2019
3. Surface movement estimation of Garhwal Himalayan Glaciers: A case study of Dokriani Glacier. Ms. Jyoti Bhatt, M.Sc. in Remote Sensing and GIS, S.S.J Campus, Almora, Kumaun University, Uttarakhand, 2019
4. Frontal Changes of Glaciers in the Nubra Valley, Karakoram, India. Ms. Sushree Subhasmita, Department of Geology, Baba Farid Institution of Technology, Dehradun, Uttarakhand, 2019
5. Glacial lake floods in the Himalayas. Ms. Subhashree Subhasmita Das, Department of Geology, Baba Farid Institution of Technology, Dehradun, Uttarakhand, 2019
6. Remote Sensing Based Assessment of Moraine-dammed Glacial Lake Changes in the Himalaya. Ms. Osheen Rai, M.Sc. in Remote Sensing and GIS, S.S.J Campus, Almora, Kumaun University, Uttarakhand, 2018.
7. Remote Sensing based assessment of Glacial Lake Changes in the Sikkim Himalaya. Rahul Yadav, M.Sc. in Environment Management, Forest Research Institute (Deemed) University, Dehradun, Uttarakhand. 2017.
8. Glacier Lake Mapping of Himachal Pradesh, India. Yatender Singh Negi, Department of Geology, SGRR (PG) College, Dehradun, Uttarakhand, 2016.
9. Glacier Changes in Chang Chenmo Valley, Karakoram. Ms. Surashree Nandi, M.Sc. in Environment Management, Forest Research Institute (Deemed) University, Dehradun, Uttarakhand, 2016.

10. Remote Sensing based pre-post event analysis of landslides in Bhagirathi valley: the June 2013 extreme event. Ms. Shweta Singh, M.Sc. in Geology, D.B.S (P.G) College, Dehradun, 2015.
 11. Climate Change in Himalaya: An Overview. Ms. Sharmila Chauhan, M.Sc. in Environmental Science, Doon University, Dehradun, Uttarakhand, 2015.
 12. Remote Sensing Based Assessment of Surge Glaciers in Karakoram. Pramod Kumar Maurya, M.Sc. in Geology, Bundelkhand University, Jhansi, UP, 2015.
-



Research article

Ice-dams, outburst floods, and movement heterogeneity of glaciers, Karakoram

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ABSTRACT

The paper concerns ice dams and glacial lake outburst floods (GLOFs) in the Karakoram. Some 146 events are identified, including 30 major disasters. Large downstream populations and major infrastructure are threatened. Risk factors differ from recent reports of other Himalayan GLOFs associated with glacier recession and global warming. Ice dams are largely or entirely active ice, put in place by advancing glaciers. Climate change is a factor, but the ice cover in the Karakoram has been sustained, and even some increase in mass. Surge-type glaciers comprise or affect ~70% of our inventory. The most frequent, large GLOFs come from local clusters of glaciers in five sub-basins, given special attention here. In four there were new ice dams formed since 2008 and two generated dangerous GLOFs. An urgent need arises to track short-term ice and lake behavior and how surge dynamics may be involved. Satellite images and DEMs are employed in cross-correlation feature tracking and elevation change respectively. The glaciers of interest all exhibit irregular movement, including recent advances, but with great variability and no clear relation to climatic fluctuations.

1. Introduction

In the upper Indus and Yarkand basins of the Karakoram, historical records of > 146 glacier lake outburst floods (GLOFs) can be traced to ice-dammed lakes (Hewitt, 1982; Hewitt and Liu, 2010; Iturrizaga, 2005c; Zhang, 1992) (Table S1 and S2). Others have been reported in neighbouring ranges including Nanga Parbat, the Hindu Raj, and Pamir Wakhan (Ashraf et al., 2017; Gruber and Mergili, 2013). The most destructive of these GLOFs brought at least 19 major disasters on the Indus, and 11 on the Yarkand (Hewitt, 2014). Some of the flood waves travelled and brought damage as much as 500 km downstream on the Yarkand, and 1200 km on the Indus. The continued occurrence of such GLOFs in the former, and indications of a 21st century resurgence of the ice dam risk for the latter, are of concern for large populations and expanding infrastructure downstream (Carrivick and Tweed, 2016).

In the impoundments of interest, glacier ice is the main or only barrier, put in place by glacier thickening or advance (Tweed, 2011). Nearly all the larger Karakoram GLOFs originate from the advance of the terminal lobe into a main, ice-free river valley of which the glacier

is a tributary (Fig. 1). These are what Ashley (Ashley, 1995) calls “ice-dammed, river-lakes”. In some cases, a thickening main glacier may impound a lake in an ice-free tributary, one of which, the Khurdopin in Shimshal, is known to generate major GLOFs (see below).

Ice dams form rapidly, rarely last more than one ablation season, when a failure occurs in all but a very few cases. Some lakes fill quickly and only survive a few weeks before draining. They may, however, be resealed several times in a given episode, if the glacier continues to advance. This is a feature of some of the most dangerous glaciers [e.g. Chong Kumdan (ID 27) 1926–33; Kyagar Glacier (ID 26) 2014–2016]. The lakes are ‘self-dumping’ (Clarke, 1986), in that drainage depends on interactions of ice barrier and lake, their dimensions, geometry and dynamic instabilities described below.

Equally, if not more significant, glacier dynamics and mass balance in the Karakoram are complicated by the many surge-type glaciers, possibly absent from the rest of the Himalaya. A large fraction of Karakoram glaciers with histories of ice dams compiled below, are surge-type (Table 1). Their behavior tends to buffer or reconfigure relations to climate (Bhambri et al., 2017). Surge-type glaciers are found

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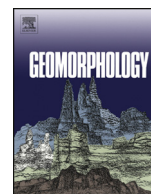
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Evolution of debris flow and moraine failure in the Gangotri Glacier region, Garhwal Himalaya: Hydro-geomorphological aspects

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ABSTRACT

A debris flow occurred in the foreland of Gangotri Glacier by its former tributary, Meru (Bamak) Glacier between 16 and 19 July 2017. We investigated the debris flow using pre- and post-event field observations; hydro-meteorological data along with remote sensing assessments to understand the mechanism and evolution of the debris flow. A large volume of sediments ($-7.9 \times 10^6 \text{ m}^3 \pm 0.1 \times 10^6 \text{ m}^3$) moved from the Meru Bamak and adjoining Neela Taal (4380 m a.s.l.) during the debris flow, depositing $6.5 \times 10^6 \text{ m}^3 \pm 0.1 \times 10^6 \text{ m}^3$ of sediments in the frontal region (4050 m a.s.l.) of the Gangotri Glacier. This event transported sediments up to 1.5 km downstream, as a debris flow fan-type feature. During the event, ~18% of the sediments were transferred by the meltwater stream. The stream of the Meru Bamak completely dissected and exposed the ice-cored left lateral moraine of the Gangotri Glacier. This event comprehensively reworked the morainic material and entirely changed the morphology of the pro-glacial area. A small pro-glacial lake (area: 5075 m²) is also observed at the snout of Gangotri Glacier because of the blockage by morainic material and sediments. A sharp increase in the concentration of suspended sediments (SSC), reaching 11,370 and 10,605 mg/l on July 18 and 19, respectively was recorded at Bhojwasa (~3 km downstream). Multiple factors such as recession of Gangotri Glacier, degraded ice-cored moraine, loose sediments at the front of the Meru Bamak, and continuous rainfall created favourable conditions for the debris flow. Therefore, geomorphic hazards associated with glacial retreat need to be investigated intensively in the Himalaya especially, in areas where significant glacial retreat is observed, lateral moraines are exposed, and the unstable slopes are occupied by the tributary glaciers.

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1. Introduction

Glacier recession and thinning because of climate change is closely associated with several types of natural hazards, which have potential to cause significant devastation (Vilímek et al., 2005; Clague et al., 2012; Huggel et al., 2012; Emmer et al., 2014; Kos et al., 2016). The hazards associated with deglaciation are mainly classified as direct and indirect dynamic slope movements (Richardson and Reynolds, 2000a; Emmer et al., 2014). Direct dynamic slope movements include snow/ice avalanches, whereas indirect movements are related with the secondary consequence of a glacial feature or process such as rock avalanches, debris flows and landslides (Emmer et al., 2014). These direct and indirect dynamic slope movements pose a high risk to the population and infrastructure in downstream areas.

Glacier recession in several high-mountain areas since the end of the Little Ice Age (LIA) have caused alteration from glacial to periglacial conditions that significantly control the sediment dynamics (Haeberli, 2013; Seppi et al., 2015; Zanoner et al., 2017). Mechanical weathering (e.g. frost shattering) and slope processes (e.g. rill and gully erosion) on moraine flanks and bank erosion at the foot of moraines frequently erode large amounts of till that consequently accumulate wide layers of unconsolidated debris. These sediments (e.g. loose boulders) covering the glacier forelands are usually affected by degradation and/or mass movement. LIA moraines are generally weak and sometimes completely or partially fail because of melting of buried ice (Haeberli and Epifani, 1986; Richardson and Reynolds, 2000a; Holm et al., 2004; Schomacker and Kjær, 2008; Tonkin et al., 2016); water pressure generated by the moraine-dammed lakes (Costa and Schuster, 1988; Clague and Evans, 2000) and debris flow generated by the sub-glacial outbursts (Mortara and Chiarle, 2005; Chiarle et al., 2007; Diolaiuti and Smiraglia, 2010; Legg et al., 2014). Loose, unconsolidated and unstable moraines

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Surge-type and surge-modified glaciers in the Karakoram

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Glaciers in the Karakoram exhibit irregular behavior. Terminus fluctuations of individual glaciers lack consistency and, unlike other parts of the Himalaya, total ice mass remained stable or slightly increased since the 1970s. These seeming anomalies are addressed through a comprehensive mapping of surge-type glaciers and surge-related impacts, based on satellite images (Landsat and ASTER), ground observations, and archival material since the 1840s. Some 221 surge-type and surge-like glaciers are identified in six main classes. Their basins cover $7,734 \pm 271 \text{ km}^2$ or ~43% of the total Karakoram glacierised area. Active phases range from some months to over 15 years. Surge intervals are identified for 27 glaciers with two or more surges, including 9 not previously reported. Mini-surges and kinematic waves are documented and surface diagnostic features indicative of surging. Surge cycle timing, intervals and mass transfers are unique to each glacier and largely out-of-phase with climate. A broad class of surge-modified ice introduces indirect and post-surge effects that further complicate tracking of climate responses. Mass balance in surge-type and surge-modified glaciers differs from conventional, climate-sensitive profiles. New approaches are required to account for such differing responses of individual glaciers, and effectively project the fate of Karakoram ice during a warming climate.

Karakoram glaciers exhibit varied and irregular ice movements^{1–3}. There is little or no synchrony of expansion or retreat for apparently similar or neighboring ice masses. Early reports suggested they are out of phase with climate fluctuations and trends observed elsewhere^{3–6}. In recent years, the Karakoram has not undergone the substantial ice mass reductions or pervasive glacier retreat observed elsewhere in the Himalaya^{6–12}. The region does have one of the world's highest concentrations of surge-type glaciers^{5,13–15} (Supplementary Table S1), the focus of this paper.

Surging refers to episodes with a sudden, large increase in ice velocities, by an order of magnitude or more in some well-documented cases¹⁶. The shift into and out of fast flow can occur in a matter of days or weeks and it may persist from a few months to several years. In a few cases surging continues for more than a decade^{16,17}. During the *active* or surge phase, large volumes of ice are transported from an upper *reservoir zone* into a lower, *receiving zone*. A wave of rapid thickening and thinning moves down-glacier, typically causing intense crevassing and over-riding of ice margin areas¹⁶. In many but not all cases, the terminus advances some kilometers in a few weeks or months^{16,18}. Between active surging there is a *quiescent phase* lasting decades to centuries when the upper glacier rebuilds mass, the lower tongue thins and retreats, or becomes stagnant. In the Karakoram and some other regions up to six distinct phases have been reported⁵ based on terms used by Jiskoot (2011)¹⁶, they are:

- (1) *A build-up phase*: when the upper glacier is growing and the lower can be stagnant or seem to behave 'normally'.
- (2) *A pre-surge phase*: when the glacier gradually speeds up and advances, possibly over several years.
- (3) *The surge or 'active' phase*: the period of fast flow.
- (4) *Post-surge deceleration and thinning*: the glacier slows gradually, crevassing and ablation zone ice levels decline. A slow advance may continue.
- (5) *Stagnation phase*: a substantial section of the ablation zone may detach and stagnate for decades usually under heavy supraglacial debris.
- (6) *Two or more active events*: rather than a single acceleration, two may occur separated by a few months or years. A short as well as much longer quiescent phase has been observed at Bualtar Glacier (ID 21).

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Devastation in the Kedarnath (Mandakini) Valley, Garhwal Himalaya, during 16–17 June 2013: a remote sensing and ground-based assessment

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Abstract The Garhwal Himalaya tragedy of 16–17 June 2013 was perhaps the worst disaster of the last century seen in India owing to unprecedented rainfall. The extreme rainfall together with bursting of moraine-dammed Chorabari Lake caused devastating flooding of the Mandakini River and its tributaries in the Garhwal Himalaya. Several downstream settlements such as Kedarnath (3546 m a.s.l.), Rambara (2740 m a.s.l.) and Gaurikund (1990 m a.s.l.) were damaged due to flash floods. The present study was taken up to assess the extent of devastation in the Mandakini Valley from Kedarnath to Sonprayag based on ground observations, repeated ground photography, discussion with local residents (eye witnesses) and analysis of pre-event and post-event high-resolution satellite data. Overall 137 ‘flash flood-induced debris flow’ events were mapped in the Mandakini Valley between Kedarnath and Sonprayag which led to the catastrophe and miseries to the pilgrims. The area of ‘flash flood-induced debris flow’ and the main channel of Mandakini River were increased by ~575 and ~406 %, respectively, during the 16–17 June 2013 event. About 50 % (7 km) of the pedestrian route (14 km) between Gaurikund and Kedarnath was completely washed away which obstructed the rescue operations to evacuate pilgrims, tourists and local people after the 16–17 June 2013 event. The ‘flash flood-induced debris flow’ and moraine-dammed lake outburst events together washed away ~120 and ~90 buildings around Kedarnath shrine and in Rambara town, respectively, although the main Kedarnath temple survived with minor damage. The database of flash flood-induced debris flows and flood effected area generated in the present research will facilitate to other disciplines (e.g., future settlements planning) for long-term reconstruction work in the affected areas of the Mandakini Valley.

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Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram

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Abstract. Glaciers in the Karakoram show long-term irregular behaviour with comparatively frequent and sudden advances. A glacier inventory of the upper Shyok valley situated in northeast Karakoram has been generated for the year 2002 using Landsat ETM+ and SRTM3 DEM as baseline data for the investigations and subsequent change analysis. The upper Shyok valley contained 2123 glaciers (larger than 0.02 km² in size) with an area of 2977.9 ± 95.3 km² in 2002. Out of these, 18 glaciers with an area of 1004.1 ± 32.1 km² showed surge-type behaviour. Change analysis based on Hexagon KH-9 (years 1973 and 1974) and Landsat TM/ETM+ (years 1989, 2002 and 2011) images had to be restricted to a subset of 136 glaciers (covering an area of 1609.7 ± 51.5 km² in 2002) due to adverse snow conditions. The area of the investigated glaciers, including the 18 surge-type glaciers identified, showed no significant changes during all studied periods. However, the analysis provides a hint that the overall glacier area slightly decreased until about 1989 (area 1973: 1613.6 ± 43.6 km²; area 1989: 1602.0 ± 33.6 km²) followed by an increase (area 2002: 1609.7 ± 51.5; area 2011: 1615.8 ± 35.5 km²). Although the overall change in area is insignificant, advances in glacier tongues since the end of the 1980s are clearly visible. Detailed estimations of length changes for individual glaciers since the 1970s and for Central Rimo Glacier since the 1930s confirm the irregular retreat and advance.

1 Introduction

Meltwater discharge from Himalayan glaciers can play a significant role in the livelihood of people living in the downstream areas. Qualitatively, glacier meltwater in the Western Himalaya and Karakoram region is less influenced by the summer monsoon compared to the central and eastern parts of the mountain chain (Immerzeel et al., 2010; Bolch et al., 2012). Recent studies revealed that most parts of northwestern Himalaya showed less glacier shrinkage than the eastern parts of the mountain range during the last decades (Bhambri and Bolch, 2009; Bolch et al., 2012; Kääb et al., 2012). Conversely, glaciers in the western and central Karakoram region showed long-term irregular behaviour with frequent advances and possible slight mass gain since the 2000s (Hewitt, 2011; Copland et al., 2011; Bolch et al., 2012; Gardelle et al., 2012, 2013; Kääb et al., 2012; Minora et al., 2013). Moreover, individual glacier advances in eastern Karakoram have also been reported in the Shyok valley during the last decade (Raina and Srivastava, 2008). These individual advances and mass gain episodes could be attributed to surging (Barrand and Murray, 2006; Hewitt, 2011; Copland et al., 2011; Quincey et al., 2011), winter temperature decrease (Shekhar et al., 2010) and increased solid precipitation in the accumulation areas (Fowler and Archer, 2006).

Copland et al. (2011) reported an increase of glacier surge activities after 1990 in the western and central Karakoram region. There are few published studies on surging phenomenon on individual glaciers such as Rimo, Chong Kumdan, Kichik Kumdan and Aktash glaciers in the eastern