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# Heterogeneity in Glacier response from 1973 to 2011 in the Shyok valley, Karakoram, India

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**Abstract**

A glacier inventory for the Shyok and Chang Chenmo basins was generated for the year 2002 using semi-automated methods based on Landsat ETM+ and SRTM3 DEM data. Glacier change analysis was carried out for 134 glaciers based on Hexagon KH-9 (years 1973, 1974) and Landsat TM/ETM+ (1989, 2002 and 2011) images. The 2002 inventory contains 2123 glaciers with an area of $2977.9 \pm 92.2\,\text{km}^2$ in the entire study area including Shyok (1605 glaciers; area $2499 \pm 77.4\,\text{km}^2$) and Chang Chenmo basins (518 glaciers; area $478.7 \pm 14.8\,\text{km}^2$). Out of 2123 glaciers, only eight glaciers have higher elevation ranges than 2000 m. On average, the glacier area in Chang Chenmo basin exhibited no changes during the study period. However, individual absolute glacier area changes varied from $-0.7 \pm 0.03\,\text{km}^2$ to $+0.2 \pm 0.01\,\text{km}^2$ between 1973 and 2011. 10 glaciers exhibited an area increase of $1.7 \pm 0.07\,\text{km}^2$ in total while 36 glaciers lost about total $1.8 \pm 0.07\,\text{km}^2$. The glacier area decreased by $11 \pm 0.47\,\text{km}^2$ from 1973 to 1989 in the Shyok basin whereas an increase in area of $8.2 \pm 0.33\,\text{km}^2$ was observed during 1989–2002. The area has further increased by $5.6 \pm 0.21\,\text{km}^2$ from 2002 to 2011 in the respective basin. This individual glacier response heterogeneity can be attributed to surging and possibly due to decreased temperature in last decades. However, further detailed studies are needed to understand glacier surge mechanism and the possible mass gain.

## 1 Introduction

Water discharge from glacier melt can be significant to livelihood of people at the downstream. Glacier melt from Western Himalaya and Karakoram is of higher importance as it is less influenced by the summer monsoon in comparison to the central and eastern parts of the mountain chain (Immerzeel et al., 2010; Bolch et al., 2012). Recent studies revealed that glaciers in Northwestern Himalaya show lesser shrinkage than the glaciers in the eastern parts of the mountain range during the recent decades;

while glaciers in the Karakoram region show long-term irregular behavior with frequent glacier advances and possible slight mass gain in the recent years (Bhambri and Bolch, 2009; Hewitt, 2011; Copland et al., 2011; Kulkarni et al., 2011; Bolch et al., 2012; Gardelle et al., 2012). Individual glacier advances have also been reported in the Shyok basin, eastern Karakoram during the last decade (Raina and Srivastva, 2008). These individual advances and mass gain phenomenon could be attributed to surging (Hewitt, 2011; Copland et al., 2011; Quincey et al., 2011) and temperature decrease in recent decades, (Fowler and Archer, 2006; Shekhar et al., 2010). Climate records of the Karakoram Himalaya show diverse trends in contrast to central and eastern Himalaya (Bolch et al., 2012).

Recent studies have reported an increase of glacier surging activities in the western and central Karakoram region (Copland et al., 2011; Hewitt, 2011). Few published studies are noteworthy on individual glaciers such as Siachen, Chong Kumdan, Kichik Kumdan and Aktash glaciers in the eastern Karakoram (Bhutiyani, 1999; Raina and Sangewar, 2007; Raina and Srivastva, 2008; Tangri et al., 2011). Periodic advances of Chong Kumdan Glacier have blocked the flow of Shyok River on several occasions and have resulted in the formation of an ice dam. Hazardous situation in downstream areas due to sudden collapse of an ice dam have been reported (Mason, 1930; Hewitt, 1982; Raina and Srivastava, 2008; Hewitt and Liu, 2011). For hazard assessment related to glacier lake outburst floods (GLOF) and for prevention of glacier hazards and to understand surging process, it is therefore essential to monitor the Karakoram glaciers frequently. However, conventional field surveys are laborious and can be dangerous in high mountainous region. Multi-spectral and multi-temporal satellite data offer abundant potential to monitor these glaciers at regular intervals. However, to the best of our knowledge there are no studies addressing planimetric changes for the larger glaciated region of the Shyok valley. Influencing variables such as topography and climate parameters are also largely unknown for this eastern part of the Karakoram. In addition till date this region remains a gap area in the Global Land Ice Measurements from Space (GLIMS) database (www.glims.org, Raup et al., 2007).





Therefore, the main goals of this study are to: (1) generate a complete and up-to date glacier inventory for the Shyok valley and to provide information on the general glacier characteristics and (2) analyze glacier area changes in Shyok valley during the last 40 yr.

## 2 Study area

The Shyok valley is a part of the Karakoram and covers the eastern part of the Upper Indus basin (UIB) (Mason, 1938). The study area Shyok basin (fourth order basin) includes glaciers of Shyok (fifth order) and Chang Chenmo (fifth order) basins as per the inventory of Indian Himalayan glaciers (Raina and Srivastava, 2008). In this study Shyok is referred as Shyok the fifth order basin unless otherwise mentioned. The Shyok River is the major tributary of the Indus River, which originates from the snout (~ 4950 m a.s.l.) of Rimo Glacier and meets Nubra River near the Tiggur (Young, 1940). This entire study area includes glaciers of the Kumdan glacier group and the Chang Chenmo valley (Fig. 1). The Rimo, Kumdan, Saser and Kunzang group of ridges form a divide between the Shyok and Nubra catchments. Our study area covers ~ 14 200 $km^2$ and has an elevation range of ~ 3600–7600 m a.s.l. Moisture derived from westerly air masses originating from Mediterranean Sea and/or Atlantic Ocean throughout the year results in comparatively high snow accumulation in the Karakoram region. This region is also influenced by precipitation from monsoon circulation during summer (Wake, 1989; Wake et al., 1990). Chemical investigations of snow and glacier ice suggest that approximately 1/3 of the total snow accumulation occurs during the summer and snow accumulation increases with elevation in the glaciated region of Karakoram (Wake, 1989). Similarly, based on cosmogenic radionuclide (CRN) dating, three glacial stages (Deshkit 1, Deshkit 2 and Dishkit 3 stages) in Nubra and Shyok valley confluence suggested that regional glacial fluctuations are controlled by the mid-latitude westerlies and oscillation in the Northern Hemisphere ice sheets and oceans (Dortch et al., 2010).



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## 3 Methodology

### 3.1 Data sources

In the present study Landsat TM/ETM+ (spatial resolution 30 m), Hexagon KH-9 (spatial resolution ~ 7 m) and OrbView 3 (spatial resolution 1 m) satellite data from United States Geological Survey (USGS, http://earthexplorer.usgs.gov/) from various years have been used to compile a glacier inventory and change analysis (Table 1). We selected an ETM+ scene of the year 2002 as reference imagery due to very little snow cover during the ablation period as compared to other scenes (Table 1). In addition, this year is close to the year 2000 for which a global glacier inventory is recommended by Paul et al. (2009) for generation of a baseline data set to facilitate glaciological applications. Since marginal areas of the studied valleys are not covered by the main Landsat scene, an additional one from September 2001 was used (Table 1). The utilized Landsat TM/ETM+ images matched well in geolocation except the 1989 TM scene which had a slight horizontal shift of ~ 30 m compared to the 2002 reference imagery. Hence, we co-registered the 1989 scene to the imagery for the year 2002 using a projective transformation algorithm. Hexagon KH-9 (1973, 1974) images were divided in 8 parts and each part were co-registered based on ~ 50 ground control points (GCPs) derived from the 2002 Landsat ETM+ imagery by spline adjustment using ESRI ArcGIS 9.3. The void-filled SRTM3 DEM from the Consortium for Spatial Information – Consultative Group for International Agriculture Research (CSI – CGIAR), version 4 (http://srtm.csi.cgiar.org/) (90 m spatial resolution) was used as a reference DEM and for semi-automatic delineation of drainage basins and extraction of topography parameters.

### 3.2 Glacier mapping, inventory and changes

Debris-free glaciers were mapped by the well established semi-automated TM3/TM5 band ratio approach followed by a 3 by 3 median filter to eliminate isolated pixels (Paul



and Kääb, 2005; Racoviteanu et al., 2009; Bolch et al., 2010; Bhambri et al., 2011). The glacier polygons derived from the median-filtered band ratio were visually checked to eliminate misclassified pro-glacial lakes, seasonal snow, rocky surfaces and shadow areas and subsequently improved manually. The identification of debris-covered termini was found to be difficult using Landsat TM/ETM+ imagery. Hence, high-resolution OrbView 3 images were used to support the identification of the glacier margin.

The contiguous ice masses were separated into their drainage basins using an automated approach for hydrological divides as proposed by Bolch et al. (2010). We assumed that the ice divides were fixed over the study period. This approach avoids errors that may occur due to different delineation of the upper glacier boundary, for instance due to varying snow conditions. The minimum size of mapped glaciers to be included in the inventory was 0.02 $km^2$. Hexagon images of the years 1973, 1974 and Landsat TM scenes of the years 1989 and 2011 were partially not suitable for glacier mapping due to fresh snow cover. Hence, we could only compare 134 glaciers (87 for the Shyok basin and 47 glaciers for Chang Chenmo basin) with a size ranging from 0.2 $km^2$ to 270 $km^2$ for spatial area variations. A total of 18 satellite scenes of Landsat TM/ETM+ and Hexagon KH-9 data scenes were used to extract the glaciers outlines of selected glaciers (Table 1). Length changes of Kichik Kumdan and Aktash were calculated using the average length of stripes with 50 m distance which were drawn parallel to the main flow direction of these glaciers (cf. Koblet et al., 2010; Bhambri et al., 2012).

Our study includes various data sources at different spatial and temporal resolutions. Thus, error assessment is crucial to determine the accuracy and significance of the results. The uncertainty was estimated for each glacier based on buffer method suggested by Granshaw and Fountain (2006). The buffer size was chosen to be half of the estimated shift caused by misregistration as only one side can be affected by the shift (Bolch et al., 2010). The buffer size of 7.5 m for the TM/ETM+ images was selected. We estimated an average uncertainty for the mapped glacier area of 3.1 % for the 2002 ETM+ imagery, 2.7 % and 2.4 % for the 1989 TM and 2011 TM images, respectively.

The glacier characteristics parameters such as minimum, maximum and median elevation, mean slope, and aspect were obtained for each glacier for the 2002 inventory based on the SRTM3 DEM. Three selected glaciers (Chong Kumdan, Kichik Kumdan and Aktash, Fig. 1) were studied in detail. The selection of glaciers is based on previous studies that have documented surging activities during last two century. This enabled us to identify surge cycles taking into account that the Kumdan glaciers have blocked the Shyok river flow several times and created hazardous situation for downstream area (Mason, 1930; Hewitt, 1982; Raina and Srivastava, 2008; Hewitt and Liu, 2011).

## 4 Results

### 4.1 Glacier characteristics

The inventory carried out for the year 2002 includes 2123 glaciers with an area of 2977.9 ± 92.2 km$^2$ in the entire study area that includes the Shyok (1605 glaciers; area 2499 ± 77.4 km$^2$) and Chang Chenmo basins (518 glaciers; area 478.7 ± 14.8 km$^2$) (Table 2). The glacier cover in the Chang Chenmo basin is about 16 % of entire glaciated study area. The median elevation of the glaciers, widely used for the estimation of long-term ELA based on topographic data (Braithwaite and Raper, 2010), ranges from 5294 to 6274 m, with an average of 5850 m in the Chang Chenmo basin. Whereas in the Shyok basin the ELA ranges from 5177 to 6450 m with an average of 5826 m. The mean glacier size is about 1.5 km$^2$ in the Shyok basin and 0.9 km$^2$ in the Chang Chenmo basin. The largest glacier covers 272.9 km$^2$ in the former and 24.3 km$^2$ in the latter basin. We identified 1255 glaciers with an area less than 1.0 km$^2$, which cover 312.2 km$^2$ in Shyok basin. This shows that small glaciers have the maximum frequency of occurrence (Fig. 2).

The glacier size classes were divided into four categories, namely, < 1, 1–5, 5–10 and > 10 km$^2$. The size class > 10 km$^2$ contains only 31 glaciers covering an area of 1297.7 ± 40.2 km$^2$ in the Shyok basin. The highest number of glaciers occur in the size



class of < 1 km$^2$, whereas glaciers > 10 km$^2$ occupy the largest area in entire study region. On average, glacier termini are 100 m lower in the Shyok basin (5572 m a.s.l.) than in the Chang Chenmo basin (5673 m a.s.l.) (Table 3). Out of 1605 glaciers in the Shyok basin, only eight glaciers have an elevation range of 2000 m region with the highest elevation range of 2876 m for north Kunchang Glacier. The average glacier elevation range is 137 m higher for the Shyok basin (475 m) as compared to the Chang Chenmo basin (338 m) (Table 3). We found no significant correlation (less then $R^2$ 0.2 for all the cases) between glacier size and median elevation or aspect in the entire study area (Fig. 3).

We identified 35 glaciers that are debris-covered in their ablation zone (Shyok basin 33 glaciers, Chang Chenmo basin 2 glaciers). In most cases, the debris is associated to medial moraines. The overall area covered by debris was about 37 km$^2$ (1.2 % of the whole ice cover) in entire study area. Most of the debris-covered glaciers parts are situated in the western section of the Shyok basin.

### 4.2 Glacier variability

On average the glaciers in the Chang Chenmo basin exhibited no change in area. However, individual absolute glacier area changes vary from −0.7 ± 0.03 km$^2$ to +0.2 ± 0.01 km$^2$ between 1973 and 2011 in the same basin. 10 glaciers exhibited an area increase of 1.73 ± 0.07 km$^2$ in total while 36 glaciers lost in total 1.78 ± 0.07 km$^2$. One glacier showed no change during 1973–2011 in this basin (Table 4). In Shyok basin 37 glaciers showed an area increase in total 10 ± 0.43 km$^2$ while 49 glaciers lost 7.2 ± 0.30 km$^2$ from 1973 to 2011. However, on average, glaciers noticeably fluctuated during 1973, 1989, 2002 and 2011 in Shyok basin. Glaciers shrank by 11 ± 0.47 km$^2$ from 1973 to 1989 in Shyok basin whereas glacier area increased by 8.2 ± 0.33 km$^2$ during 1989–2002 and increased further by 5.6 ± 0.21 km$^2$ from 2002 to 2011 (Table 5).

It was found that there is no significant statistical relationship (less then $R^2$ 0.3 for all the cases) between glacier area change (1973–2011) and topographic parameters such as minimum, maximum, median, mean, aspect and range elevation in entire study area (Fig. 4).

Kichik Kumdan Glacier lost ∼5.2 % of its area during 1974 to 1989 but grew by strongly (∼5.2 %) from 1989 to 2002. More recently (2002–2011), the glacier diminished again by ∼1.3 % (Table 6). However, the adjacent Aktash Glacier showed a different behaviour during the same period. This glacier shrank by only 0.5 % between 1974 and 1989 and exhibited a slight area gain of about 1.2 % from 1989 to 2002. Between 2002–2011, the area of the glacier increased further by 2.8 %.

## 5 Discussion

### 5.1 Glacier inventory and changes

We mapped 2123 glaciers in entire study area including the Shyok (1605 glaciers; area 2499 ± 77.4 $km^2$) and Chang Chenmo basins (518 glaciers; area 479 ± 14.8 $km^2$) for the 2002 inventory. Geological Survey of India (GSI) reported 955 (area 2300 $km^2$) and 308 glaciers (area 557 $km^2$) in Shyok and Chang Chenmo basins respectively. This difference can be attributed to the inclusion of smaller glaciers with a minimum threshold of 0.02 $km^2$ in the present glacier inventory but the omission of smaller ice bodies in case of the GSI inventory. The GSI glacier inventory for the Shyok basin is based on 1 : 50 000 scale Survey of India (SOI) topographic maps, aided by satellite images and aerial photographs with limited field checks (Raina and Srivastava, 2008; Sangewar and Shukla, 2009). These SOI topographic maps do not show all ice bodies due to scale limitations. In addition, the glaciers might have been misinterpreted due to seasonal snow and debris cover (Raina and Srivastava, 2008; Bhambri and Bolch, 2009). The objective of a study has an influence on the glacier count. Contiguous ice masses can be counted as a single entity or can be subdivided into multiple glaciers. In this study, the mapping method and inventory standards for digital data source proposed by Paul et al. (2009) and Racoviteanu et al. (2009) has been adopted and topographic





information (e.g. aspect, mean slope, and elevation) and the portion of debris cover is included in the data base which will be available through GLIMS.

All glaciers observed in the entire study area are almost debris free (2088 count; area: 2941 $km^2$) and only about 1 % of the glaciers area (35 glaciers; area: 36.9 $km^2$) are covered with debris. This is likely due to local lithology (Karakorum plutonic complex) of rocks in the Shyok basin and the fact that most of the headwalls are covered with ice and are broader and not so steep as compared to regions with a high percentage of debris-cover (for example Garhwal or Khumbu Himalaya). In addition, a negative mass budget and area loss favors the increase of debris cover on glaciers (Bolch et al., 2008; Stokes et al., 2007) while the investigated glaciers are more stable in Shyok basin. The high-resolution OrbView 3 satellite images were used to verify the interpretation of debris-covered tongues. We could study glacier changes for 134 glaciers only owing to fresh snow in 1989 and 2011 Landsat TM satellite images.

Here we report for the first time that there are evidences of slight but significant glacier area gain in recent decades [1973–1989: −11.3 ± 0.45 $km^2$ (−0.7 %); 1989–2002: +8.1 ± 0.33 $km^2$ (+0.5 %); 2002–2011: +6 ± 0.23 $km^2$ (+0.37 %)] in the eastern Karakoram region. This is in line with Gardelle et al. (2012) who reported a slight, insignificant, mass gain in the central Karakoram. These advances in glacier area can mainly be attributed to known surging activity of the glaciers of the area. Previous studies in Garhwal Himalaya (Dobhal et al., 2008; Bhambri et al., 2011; Mehta et al., 2011), Himachal Himalaya (Kulkarni et al., 2007) have reported an increase in number of glaciers during last few decades due to disintegration whereas we found some glaciers coalesced after surging process in eastern Karakoram region. This suggests that the Karakoram area is showing a different response to climate change than other parts of the Himalaya as noted by Hewitt (2005) and Gardelle et al. (2012).

Complex image geometry impends upon rectification process of Hexagon images. This is possibly main source of uncertainty in our estimates of glacier change. However, Hexagon images from the 1970s are helpful to identify surge events and provide insight into long term behavior of glaciers in remote and inaccessible areas in the absence of historic (since 1970s) aerial photographs and are useful to evaluate inventories based on topographic maps (Bhambri and Bolch, 2009).

### 5.2 Surging glaciers in Shyok Valley

Our results show that figures (number and area) of glacier advancement in Chang Chenmo and Shyok basins changed frequently during study period (Table 4). The analysis of satellite data of 1973, 1989 and 1998 to 2011 (every year satellite data, 14 scenes) suggest that Chong Kumdan Glacier began surging from 2002 and continued to surge until 2011. Grant and Mason (1940) predicted that this glacier is likely to obstruct Shyok river and form a large lake in 1970s, and again can advance by 2013. However, fortunately this glacier could not block Shyok river during study period. In case of Kichik Kumdan Glacier, our study using Corona (1973, 1974) images show that the front of Kichik Kumdan is touching the Shyok river (Fig. 5). However, no evidence of obstruction is seen as yet, but the glacier is potentially vulnerable to surging and related events. This glacier retreated on average ~553 m during 1974 to 1989 and ~496 m from 1989 to 1998. During 1998–1999, this glacier shows sudden advance of ~975 m and ~272 m advance in 2000 and till 2004 this glacier front did not change (Fig. 6). During 2004 to 2011 this glacier again shows retreat of ~287 m. The Aktash Glacier was almost stable during 1974 to 1989 and terminates ~210 m away from the Shyok River. This glacier advanced by ~110 m from 1989 to 1998 and during 2002/2003 touched the river and crossed the Shyok River in 2009 (Fig. 7). The river tunneled the glacier front from its bottom and continued to flow without any blockage.

Several studies have reported periodic surging during the last two centuries and its effect downstream of Kumdan glaciers (Table 7). The lakes formed due to blockage, periodically burst and discharge huge amounts of water to downstream areas (Mason, 1929; Mason et al., 1930). Hewitt and Liu (2010) reported historic events of about 90 ice-dammed lakes associated to a dozen of glaciers and outburst floods in entire Karakoram while Copland et al. (2011) reported 90 surge events in entire Karakoram from 1960s onwards. The number of surges has almost doubled after 1990





which can be due to the hydrological control (Quincey et al., 2011) and thermal control (Copland et al., 2011). In addition, surging glaciers have all-year accumulation regime, avalanche nourishment, and increase snow effects related to elevation in accumulation zones which could be the possible reasons of mass gain and sudden advance in recent decades (Hewitt, 2011). Few existing meteorological observations in eastern Karakoram show a decrease by 1.6 and 3.8 °C in winter maximum and minimum temperatures, respectively during 1984/85 to 2007/08 while the decreasing trend in total seasonal snowfall over this part of Karakoram range is only ~40 cm (Shekhar et al., 2010). However, the existing stations are situated in valley bottoms and may not be representative for the glaciated regions. The periodic advancement of Chong Kumdan, Kichik Kumdan and Aktash glaciers in recent years suggests that there is an urgent need to monitor the surging process and lake formation on a regular basis.

Heterogeneous glacier response in Shyok valley to climate change remains mystical mainly due to the lack of long-term programs of field mass balance and the unavailability of long term climate data near the glaciers. However, ongoing studies on multi-temporal measurement of surface flow before, during, and post surge events by remote sensing will provide data to infer surge cycles and its controlling mechanism in Shyok basin (cf. Quincey et al., 2011). Volumetric glacial changes by temporal analysis of DEMs along with velocity results will also give insights to understand glacier surge mechanism and mass gain.

## 6 Conclusions

Our inventory of ~2100 glaciers of eastern Karakoram region and detailed change analysis of 134 glaciers for the period 1973–2011 using Hexagon KH-9 and Landsat imageries will not only fill the gaps in GLIMS database but also support further detailed studies related to volumetric changes, surging mechanism and lake outburst modelling of ice-dammed lakes. The study shows for the first time significant glacier area gain in recent decades in the eastern Karakoram region. Hexagon KH-9 from



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the 1970s allowed mapping of older positions of glaciers. Fresh snow cover and cloud cover hamped the generation of multi-temporal glacier inventories for the entire region. Glaciers in the Chang Chenmo basin show on average no change in glacier area during the study period. Whereas in Shyok basin glaciers shrank by $11.0 \pm 0.47\,km^2$ from 1973 to 1989 and during 1989–2002 glacier area increased by $8.2 \pm 0.33\,km^2$ and increased further more recently by $5.6 \pm 0.21\,km^2$ from 2002 to 2011 in this basin. This heterogeneous response of glaciers in the Shyok basin with surge activities is similar to other western Karakoram glaciers. However, the complex glacier surge mechanism and mass gain need to be further investigated by field investigations, geodetic mass budget estimations and glacier flow studies.

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**Table 1.** Details of the USGS satellite data used in the present study.

| Year | Scene ID | Satellite/Sensor | Purpose |
|---|---|---|---|
| 1973-11-19 | DZB1207-500030L012001 | Hexagon KH 9/ Panchromatic Camera | For glacier change in selected 134 glaciers |
| 1974-11-16 | DZB1209-500081L013001 | | |
| 1989-10-09 | p147r36_5t19891009 | Landsat 5/ TM, Landsat 7/ ETM+ | For glacier change in selected 134 glaciers |
| 1998-09-16 | L5147036_03619980916 | | For detailed glacier change in the study area |
| 1999-10-29 | L71147036_03619991029 | | |
| 2000-08-28 | L71147036_03620000828 | | |
| 2001-09-25 | LE71460362001268EDC00 | | |
| 2002-08-02 | L71147036_03620020802 | | For glacier inventory in the study area |
| 2003-09-22 | L71147036_03620030922 | | For detailed glacier change in the study area |
| 2004-09-08 | L71147036_03620040908 | | |
| 2005-10-29 | L71147036_03620051029 | | |
| 2006-02-09 | 3V060209P0001088391A 520008601082M_001620696_1GST | OrbView-3 (PAN) | For detailed glacier change in the study area and debris-covered ice mapping |
| 2006-09-30 | L71147036_03620060930 | Landsat 5/ TM, Landsat 7/ETM+ | For detailed glacier change in the study area |
| 2007-08-16 | L71147036_03620070816 | | |
| 2009-09-30 | L5147036_03620090930 | | |
| 2010-09-17 | L5147036_03620100917 | | |
| 2010-10-03 | L5147036_03620101003 | | |
| 2011-08-03 | L5147036_03620110803 | | For glacier change in selected 134 glaciers |



**Table 2.** Size-wise area and number of glaciers in Chang Chenmo and Shyok basin.

| Study area | Chang Chenmo basin (A) | | Shyok basin (B) | | Entire study area (A+B) | |
|---|---|---|---|---|---|---|
| Area by glacier size (km$^2$) | (km$^2$) | Number of glaciers | (km$^2$) | Number of glaciers | (km$^2$) | Number of glaciers |
| < 1 | 86.7 ± 2.6 | 428 | 312.2 ± 9.6 | 1255 | 398.9 ± 12.2 | 1683 |
| 1–5 | 164.1 ± 5.0 | 68 | 586.3 ± 18.1 | 278 | 750.5 ± 23.1 | 346 |
| 5–10 | 83.7 ± 2.6 | 12 | 302.9 ± 9.3 | 41 | 386.6 ± 11.9 | 53 |
| > 10 | 144.0 ± 4.4 | 10 | 1297.7 ± 40.2 | 31 | 1441.7 ± 44.6 | 41 |
| Total | 478.7 ± 14.6 | 518 | 2499.1 ± 77.4 | 1605 | 2977.9 ± 92.0 | 2123 |





Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

**Table 3.** Derived glacier parameters from SRTM3 DEM and 2002 August Landsat ETM+ imagery for the Chang Chenmo and Shyok basins.

| Study area | Chang Chenmo basin (A) | Shyok basin (B) | Entire study area (A+B) |
|---|---|---|---|
| Average Elevation Minimum (m) | 5672.8 | 5572.2 | 5596.8 |
| Average Elevation Maximum (m) | 6010.6 | 6046.9 | 6038.0 |
| Average Elevation Mean (m) | 5849.7 | 5824.8 | 5830.9 |
| Average Elevation Median (m) | 5850.2 | 5825.8 | 5831.8 |
| Average Elevation Range (m) | 337.8 | 474.6 | 441.2 |
| Average Slope (deg° ) | 24.8 | 28.1 | 27.3 |



**Table 4.** Variability of the investigated glaciers in Chang Chenmo and Shyok basin 1973–2011.

| Year | Chang Chenmo basin | | | | | Shyok basin | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Advanced | | Retreat | | No change | Advanced | | Retreat | | No change |
| | Nos. | Area (km$^2$) | Nos. | Area (km$^2$) | Nos. | Nos. | Area (km$^2$) | Nos. | Area (km$^2$) | Nos. |
| 1973–1989 | 6 | 0.91 | 31 | 1.2 | 10 | 21 | 3.1 | 55 | 14.2 | 11 |
| 1989–2002 | 17 | 0.93 | 26 | 0.94 | 4 | 46 | 10.6 | 34 | 2.5 | 7 |
| 2002–2011 | 13 | 0.82 | 22 | 0.56 | 12 | 37 | 10.2 | 26 | 4.6 | 24 |
| 1973–2011 | 10 | 1.73 | 36 | 1.78 | 1 | 37 | 10.0 | 49 | 7.2 | 1 |




Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

**Table 5.** Changes in ice area in the study area between 1973, 1989, 2002 and 2011based on Hexagon and Landsat images.

| Region | Area ($km^2$) | | | | 1973–1989 | | | 1989–2002 | | | 2002–2011 | | | 1973–2011 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1973 | 1989 | 2002 | 2011 | Δ ($km^2$) | Δ (%) | Δ/a (%) | Δ ($km^2$) | Δ (%) | Δ/a (%) | Δ ($km^2$) | Δ (%) | Δ/a (%) | Δ ($km^2$) | Δ (%) | Δ/a (%) |
| Chang Chenmo basin (A) | 200.6 ± 6.0 | 200.38 ± 5.4 | 200.37 ± 6.2 | 200.62 ± 4.8 | −0.2 ± 0.008 | −0.09 | – | −0.01 ± 0.0004 | −0.004 | – | +0.25 ± 0.009 | +0.1 | – | – | – | – |
| Shyok basin (B) | 1406.4 ± 42.1 | 1395.4 ± 37.6 | 1403.6 ± 43.5 | 1409.2 ± 33.8 | −11 ± 0.44 | −0.78 | −0.04 | +8.2 ± 0.33 | +0.5 | +0.03 | +5.6 ± 0.21 | +0.39 | +0.04 | +2.8 ± 0.12 | +0.2 | +0.005 |
| Entire study area (A+B) | 1607.1 ± 48.2 | 1595.8 ± 43.0 | 1603.9 ± 49.7 | 1609.9 ± 38.6 | −-11.3 ± 0.45 | −0.7 | −0.04 | +8.1 ± 0.33 | +0.5 | +0.03 | +6 ± 0.23 | +0.37 | +0.05 | +2.8 ± 0.12 | +0.17 | +0.004 |





**Table 6.** Length and area fluctuation of Kichik Kumdan and Aktash glaciers during study period.

| Kichik Kumdan Glacier/Year | Area ($km^2$) | Absolute area change ($km^2$) | Relative area change (%) | Relative area change rate (% $yr^{-1}$) | Retreat/ advance (m) | Retreat/ advance (m $yr^{-1}$) |
|---|---|---|---|---|---|---|
| 1974 | 67.0 | | | | | |
| 1989 | 63.5 | −3.5 | −5.2 | −0.34 | −553 | −36.8 |
| 1998 | 62.6 | −0.9 | −1.4 | −0.15 | −496 | −55.1 |
| 1999 | 66.0 | +3.4 | +5.4 | +5.4 | +975 | +975 |
| 2000 | 66.9 | +0.9 | +1.3 | +1.3 | +272 | +272 |
| 2002 | 66.8 | −0.1 | −0.1 | −0.05 | – | – |
| 2004 | 66.8 | – | – | – | – | – |
| 2011 | 65.9 | −0.9 | −1.3 | −0.18 | −287 | −41 |
| 1974–1989 | | −3.5 | −5.2 | −0.34 | −553 | −36.8 |
| 1989–2002 | | +3.3 | +5.2 | +0.4 | +552 | +42.4 |
| 2002–2011 | | −0.9 | −1.3 | −0.14 | −287 | −31.8 |
| **Aktash Glacier/Year** | **Area ($km^2$)** | **Absolute area change ($km^2$)** | **Relative area change (%)** | **Relative area change rate (% $yr^{-1}$)** | **Retreat/ advance (m)** | **Retreat/ advance (m $yr^{-1}$)** |
| 1974 | 26.67 | | | | | |
| 1989 | 26.53 | −0.14 | −0.52 | −0.03 | −138 | −9.2 |
| 1998 | 26.83 | +0.30 | +1.13 | +0.12 | +106 | +11.7 |
| 1999 | 26.84 | +0.01 | +0.03 | +0.03 | +29 | +29 |
| 2000 | 26.84 | – | – | – | – | – |
| 2002 | 26.86 | +0.02 | +0.07 | +0.03 | +47 | +23.5 |
| 2006 | 26.90 | +0.04 | +0.14 | +0.03 | +80 | +20 |
| 2008 | 26.95 | +0.05 | +0.18 | +0.09 | +100 | +50 |
| 2009 | 27.32 | +0.37 | +1.37 | +1.37 | +207 | +207 |
| 2011 | 27.62 | +0.30 | +1.1 | +0.55 | +212 | +70.6 |
| 1974–1989 | | −0.14 | −0.52 | −0.03 | −138 | −9.2 |
| 1989–2002 | | +0.33 | +1.2 | +0.09 | +183 | +14.0 |
| 2002–2011 | | +0.76 | +2.8 | +0.31 | +599 | +66.5 |

**Table 7.** Glacier lake outbursts in Shyok River (Source: Hewitt and Liu, 2010).

| Year | Glacier | River dammed | Comment |
|---|---|---|---|
| 1533 | Kumdan | Shyok | No details |
| 1780 (approx.) | Kumdan | Shyok | No details |
| 1826 | Kumdan | Shyok | Serious flooding |
| 1833a | Kumdan | Shyok | Mountains only |
| 1835 | Sultan Chussku | Shyok | Extensive floods |
| 1839 | Kumdan | Shyok | Less than 1835 |
| 1842 | Chong Kumdan | Shyok | Small |
| 1855a | Kumdan | Shyok | Damage at Gol |
| 1855b | Kumdan | Shyok | Major flood |
| 1871 | Kumdan | Shyok | Large flood (Nov) |
| 1879(?) | Kumdan | Shyok | Great flood (Aug) |
| 1882a | Kumdan | Shyok | Largest flood (Jul) |
| 1898 | Kumdan | Shyok | Large flood (Jul) |
| 1901a | Kumdan | Shyok | Major flood (May) |
| 1903b | Kichik Kumdan | Shyok | Local flooding |
| 1905a | Kichik Kumdan | Shyok | Small flood |
| 1926 | Chong Kumdan | Shyok | Great flood (Oct) |
| 1929 | Chong Kumdan | Shyok | Great flood (Jul) |
| 1932 | Chong Kumdan | Shyok | Major flood (Oct) |
| 1933 | Chong Kumdan | Shyok | Major flood (Aug) |



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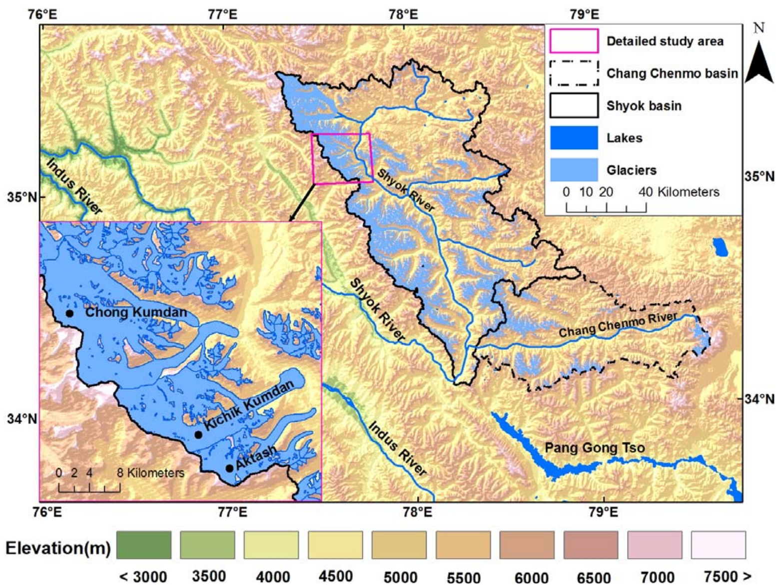


**Fig. 1.** Overview of the Chang Chenmo and Shyok basin showing Karakoram with the three glaciers. Glacier outlines derived from 2002 August Landsat TM imagery. Color elevation background presented by SRTM3 data.

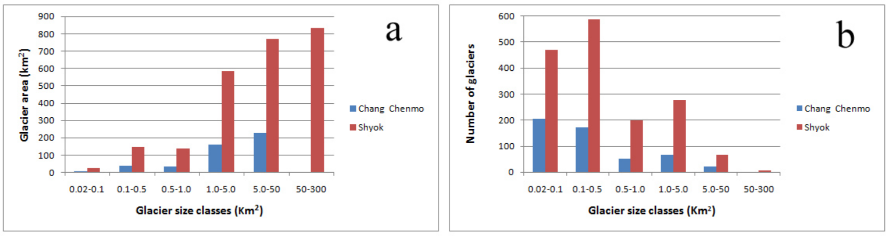


**Fig. 2.** Diagram showing the size class wise distribution of glaciers in Chang Chenmo and Shyok basin **(A)** glacier size class vs. glacier area and **(B)** glacier size class vs. number of glaciers.



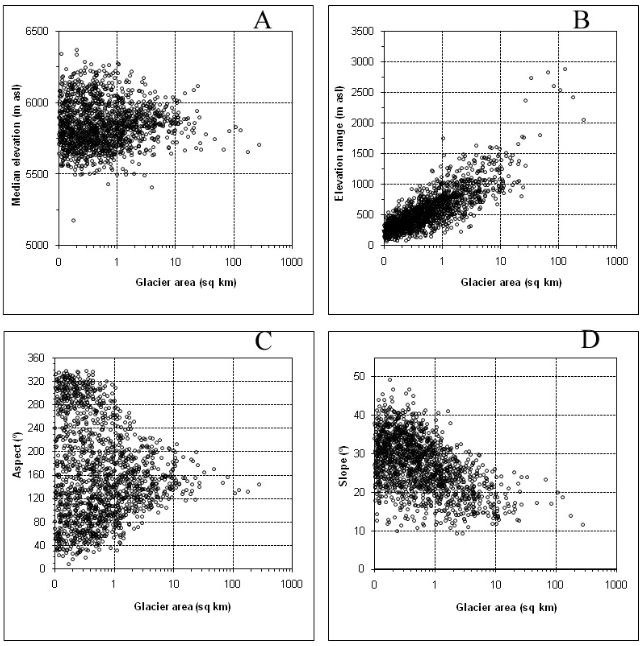


**Fig. 3.** Scatter plots of **(a)** glacier area vs. median elevation, **(b)** glacier area vs. elevation range, **(c)** glacier area vs. aspect and **(d)** glacier area vs. slope. Glacier area and inventory data derived from Landsat TM (2002-08-02) imagery and SRTM DEM respectively.




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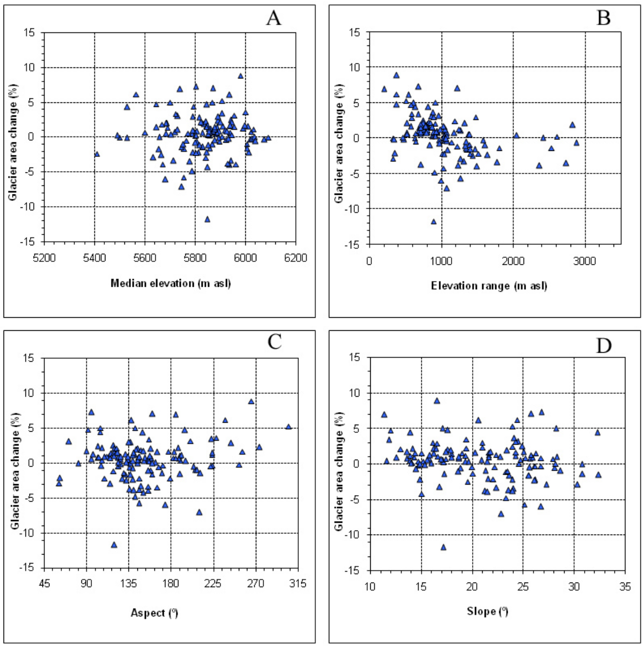


**Fig. 4.** Scatter plots of **(a)** median elevation vs. glacier area change (%), **(b)** elevation range vs. glacier area change (%), **(c)** aspect vs. glacier area change (%) and **(d)** slope vs. glacier area change (%). Glacier area change (%) derived from analysis of Hexagon (1973-11-16) and Landsat TM 2011-08-03 images. Inventory data derived from SRTM DEM.





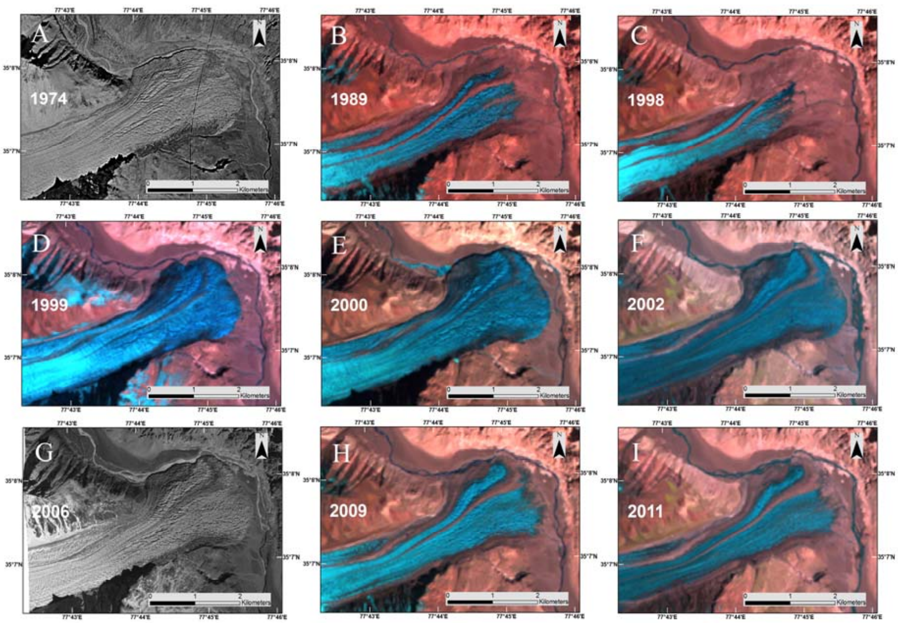


**Fig. 5.** Kichik Kumdan Glacier fluctuation during study period **(A)** Hexagon (1974-11-16), **(B)** Landsat TM (1989-10-09), **(C)** Landsat TM (1998-09-16), **(D)** Landsat TM (1999-10-29), **(E)** Landsat ETM+ (2000-08-28), **(F)** Landsat ETM+ (2002-08-02), **(G)** OrbView-3 (2006-02-09), **(H)** Landsat TM (2009-09-30), **(I)** Landsat TM (2011-08-03). Hexagon and OrbView-3 are panchromatic images and Landsat TM and ETM+ band combination is 5-4-3.

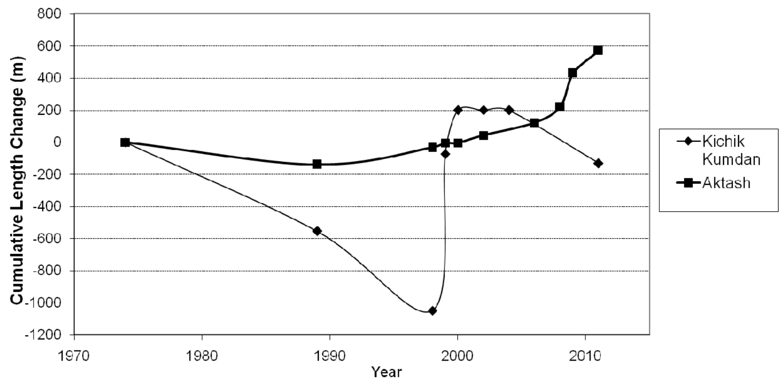


**Fig. 6.** Cumulative length records of Kichik Kumdan and Aktash glaciers during 1974–2011.



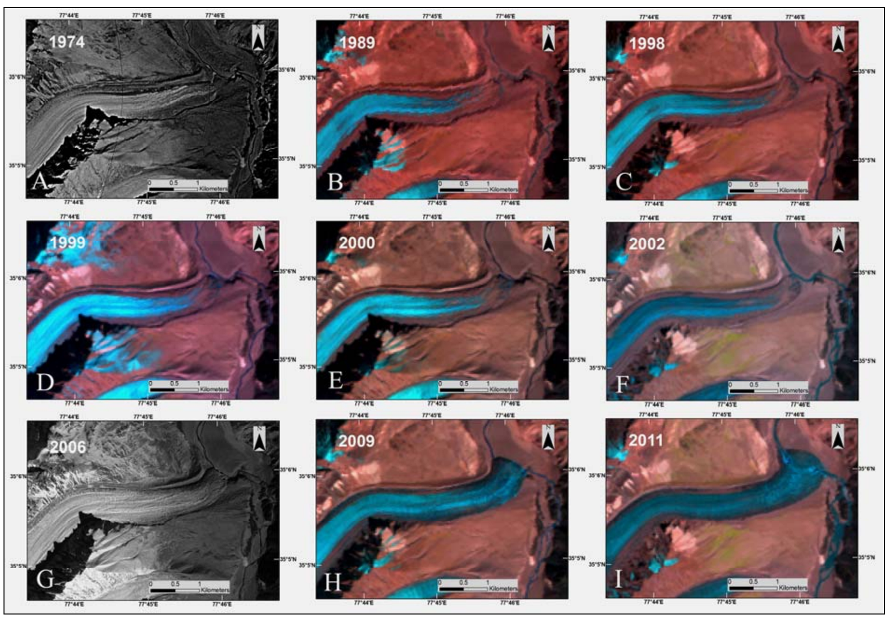


**Fig. 7.** Aktash Glacier fluctuation during study period **(A)** Hexagon (1974-11-16), **(B)** Landsat TM (1989-10-09), **(C)** Landsat TM (1998-09-16), **(D)** Landsat TM (1999-10-29), **(E)** Landsat ETM+ (2000-08-28), **(F)** Landsat ETM+ (2002-08-02), **(G)** OrbView-3 (2006-02-09), **(H)** Landsat TM (2009-09-30), **(I)** Landsat TM (2011-08-03). Hexagon and OrbView-3 are panchromatic images and Landsat TM and ETM+ band combination is 5-4-3.