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Satellite monitoring of glaciers in the Karakoram from 1977 to 2013: an overall almost stable population of dynamic glaciers

R. M. Brahmbhatt[1], I. M. Bahuguna[2], B. P. Rathore[2], S. K. Singh[2], A. S. Rajawat[2], R. D. Shah[1], and J. S. Kargel[3]

[1]M.G. Science Institute, Ahmedabad, India
[2]Space Applications Centre, ISRO, Ahmedabad, India
[3]Department of Hydrology & Water Resources, University of Arizona, Tucson, AZ, USA

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Correspondence to: R. M. Brahmbhatt (rupal.brahmbhatt@gmail.com)

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Abstract

Six hundred and seven glaciers of the Shigar, Shashghan, Nubra and part of Shyok sub-basins of the Karakoram region were monitored using satellite data of years 1977, 1990, 2000, 2001, 2002, 2004, 2006, 2008, 2009, 2010, 2011 and 2013. Landsat MSS, TM, ETM+ and IRS/Resourcesat-1 LISS III data were used. Glacier observations were classified into 3 categories such as advance, retreat or stable with reference to base data of 1977. Glaciers of the Karakoram have shown inconsistency in advance, retreat and no change during this period, and some examples of glacier surging have been caught in action. Despite significant geographic and temporal variability betraying the dynamic nature of many of the glaciers, in aggregate the population is roughly stable with less propensity toward retreat than most other glaciers in the nearby Himalaya and in the world. 341 glaciers exhibited no measured change throughout the 36 years of the study. Among other glaciers, no significant and sustained pattern of retreat or advance was observed. The overall changes in glacier area in the whole region are of small magnitudes (positive and negative values) in the various measured intervals. Moreover, it is mostly disconnected glaciers in tributary valleys which have advanced, whereas the main former trunk glaciers have primarily not changed. The dynamical differences between disconnected former tributaries and trunks may be related to response time differences, with the smaller, perhaps steeper tributaries responding more rapidly than trunks to brief climatic fluctuations. The advance/retreat fluctuations of many individual glaciers suggest that their response times primarily may be of order decades rather than some longer period, though some glaciers may have longer response times that have limited their length and area changes over the 36 year study period. The data from 2001 onwards were also utilized for finding annual changes of glaciers. Among the 607 glaciers, 10 show considerable fluctuation in their area; in several cases surge-waste cycles appear to be active. Glacier thickness change measurements are needed to aid our understanding of the regional glacier dynamics and relationships to climate change and area-response dynamics.

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1 Introduction

In most satellite-based and in situ studies of glaciers in the Himalaya and most other parts of High Asia, it is reported that there is a general glacier recession or thinning and mass loss (Berthier et al., 2007; Kulkarni et al., 2007, 2014; Dobhal et al., 2008; Velicogna et al., 2009; Cazenave and Chen, 2010; Matsuo and Heki, 2010; Bhambri et al., 2011, 2012; Bolch, et. al., 2011, 2012; Fujita and Nuimura, 2011; Kargel et al., 2011; Scherler et al., 2011; Brahmbhatt et al., 2012; Jacob et al., 2012; Schmidt and Nusser, 2012; Venkatesh et al., 2012; Yuning and Freymueller, 2012; Gardelle et al., 2013; Kulkarni and Karyakarte, 2014; Racoviteanu et al., 2014a, b; Bahuguna et al., 2014). The assessed rates of retreat or mass loss differ greatly between glaciers and among sub regions. It is generally now agreed, contrary to widespread older speculations that Hindu-Kush/Karakoram/Himalaya (HKH) glaciers were losing mass unusually rapidly, that the rates of thinning and mass loss in the HKH are typical of the rates around the world (Cogley et al., 2010), and that some parts of this region, particularly the Karakoram, have complex patterns of retreating/thinning, stable, and even growing glaciers (Hewitt, 2005; Kargel et al., 2005; Bolch et al., 2012; Gardelle et al., 2012, 2013; Kääb et al., 2012; Bhambri et al., 2013; Racoviteanu et al., 2014a, b). Our present work reinforces this more nuanced emergent understanding of glacier change in the HKH and adds news details on the temporal evolution of the region's glaciers derived from a new methodological approach to the matter.

Recently, the mass balance was determined gravimetrically for the last decade for the various climatic zones of High Asia, which shows that loss of mass was higher in western Himalaya in comparison to the eastern and central Himalaya (Gardelle et al., 2013). Moreover, glacier ice loss was estimated as a maximum in Jammu-Kashmir region for the 21st century (Kaab et al., 2012). In addition, the Ganges, Indus and Brahmaputra basins, the glacier contribution was estimated to make up about 10 % of the current glacier contribution to sea-level rise (Kaab et al., 2014). Contrary to the general world and Himalayan trend of deglaciation, several studies of glaciers of the

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Karakoram have shown the advances or surges of snouts. This was first brought into notice by Hewitt, in his article "The Karakoram anomaly" (Hewitt, 2005). Supporting this concept, slight mass gain has occurred in the Karakoram in the 21st century, and this has been attributed to glacier growth (Gardelle et al., 2012). Mayer has carried out detailed field studies of the ablation zone of Baltoro glacier in 2004 (Mayer et al., 2006). In addition, he has reported a surge-like event of North Gasherbrum Glacier on the northeastern slope of the Karakoram Mountains between 2003 and 2007 based on Landsat ETM+ images from 2000 to 2009 (Mayer et al., 2011). Copland determined surface velocities of major glaciers across the central Karakoram using optical matching of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image pairs (Copland et al., 2011). Moreover, Minora measured area change of more than 700 glaciers for the period of 2001–2010 in the Central Karakoram National Park (Minora et al., 2013). The inventory of glaciers and velocity were measured using multi-mission satellite images. The change in glaciers was estimated using two time frames (1976–2012), in which they have shown that 80 % of glaciers have remained stable during this monitoring period (Rankl et al., 2014). The composite of studies has now made a complete inventory of glaciers from the entire HKH, and these data are now in the GLIMS (Global Land Ice Measurements from Space) glacier database. Taking cue from this progress, we have determined the changes in Karakoram glaciers using multi-temporal images acquired from 1977 to 2013. The analyzed intervals are 1977 to 1990, 1990 to 2001, 2001 to 2010, and 2010 to 2013. Considering the seeming contradictory or ambiguous (or at least confusing) collection of results obtained for Karakoram glaciers by many previous studies (reviewed by Kääb et al., 2014), this new temporal resolution of glacier changes is very needed. Image resolution relative to changes remains a serious limitation for this type of study, especially for the earlier periods, but we have done the best we could with the available imagery.

2 Data and methodology

Multi-year Landsat MSS (Multispectral Scanner), Landsat TM (Thematic Mapper)/ETM+ (Enhanced Thematic Mapper), and LISS III (Linear Imaging Self-Scanner) images have been used for this study. The MSS data have 68 m × 83 m spatial resolution and four spectral bands: Green (0.5–0.6 µm), Red (0.6–0.7 µm), Near Infrared (0.7–0.8 µm), and Near Infrared (0.8–1.1 µm). The dates of the various satellite images have been given in Table 1. The Landsat data of the TM sensor have seven bands, each with a spatial resolution of 30 m, except thermal infrared, which is 120 m. Landsat ETM+ has 30 m spatial resolution, except the panchromatic band with 15 m and thermal infrared band with 60 m resolution. IRS LISS III images have four spectral bands: band 1 (0.52–0.59 µm), band 2 (0.62–0.68 µm), and band 3 (0.77–0.86 µm) at 23.5 m resolution and band 4 (1.55–1.70 µm) at 56 m (only for 2001) resolution. The images were chosen to minimize snow and cloud cover during the glaciers' ablation period. The false-color composites of bands in VNIR of LISS-III data were georeferenced with the corresponding ortho-rectified Landsat data. While executing georeferencing, we applied the same datum and projection to the images. The ERDAS IMAGINE version 9.1was used for the pre-processing of digital images. Then vector layers of glacier extents were prepared by on-screen digitization. The change detection of extents was carried out using these vector layers.

Purely automated mapping is not yet technically feasible due to obscuring effects of partial debris cover. Mapping from images requires use of elements of visual interpretation, such as the unique reflectance of snow and ice, the shape of the valley occupied by the glacier (particularly changes in slope at the glacier edges), the flow lines of ice movement inferred from medial moraines in single scenes or feature displacement in multi-temporal images, the rough texture of debris-covered parts of the ablation zone, and the presence of vegetation on non-glacier areas. The SWIR band is also used to discriminate snow and clouds. The advance, retreat, or stability of the snout of a glacier is the most important feature for monitoring of glaciers. However, the snouts of many

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glaciers are not distinct due to debris cover and degradation of the tongue. In such cases various other indicators helped in identification, such as location of the origin of a stream from the glacier's terminus or presence of distinct geomorphic features in the form of braided streams, lakes, glacio-fluvio sands etc. In the periglacial area around snouts, changes of slope or elevation near the snout may be discerned using DEMs from SRTM. For detection of changes in area of glaciers, only the change around the snout area (within the ablation zones) were considered as the accumulation zone is very dynamic in terms of snow cover, and net change in the glacier area is reflected most clearly near the snout. Care was taken to see that changes in the extent do not cross over former lateral moraines.

3 Estimation of uncertainties

Raup et al. (2014) conducted a set of Glacier Comparison Experiments (GLACE) to assess the full combined set of errors when different people map the same glaciers using either different or the same types of remote sensing data. The uncertainties – assessed by divergence of mapping results – were surprisingly large due mainly to human subjective errors along debris-covered parts of glacier margins.

We have minimized errors by making use of a consistent measurement approach applied to similar types of multispectral image data by a single analyst (the first author). It is important to make very clear our methodology. We computed uncertainties of glacier areas and glacier area changes from the random error formulations adapted from the treatment given by Krumwiede et al. (2014). It is important to distinguish the problem of uncertainty of area change limited by measurement *precision* of the snout area made by a consistent methodology and a single analyst (which is what pertains here to assessed changes) vs. the *accuracy* of total glacier area measurements made by different methodologies and using different analysts (which is mainly what the GLACE experiments investigated). It is thus a problem similar to that of high-precision measurements used to detect *changes* in quantities whose total magnitudes are less

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reliably known to such high precision, for example, in mass spectrometry, stellar luminosity measurements, or employment statistics. Detection of extra solar planets and radiometric dating of rocks would not have been possible without recognition of this distinction between precision and accuracy; nor would the area changes of Karakoram glaciers be measureable without this single-analyst approach. The reproducibility of area-change results by another analyst should, however, be possible, though the total glacier areas measured by the two analysts would presumably be different, as the GLACE experiments would indicate.

Clearly *precision* of change as defined here can be much better than absolute *accuracy* of the whole. Furthermore, in reference to glaciers, precision of glacier area-change measurements made using a uniform approach can be much better than area-change measurements assessed by using two independent measurements using different methodologies, for example from two independent inventories made from totally different data types, different approaches, and different analysts. It should be clear that our fundamental measurements were not of total glacier area, but of changed snout area. This distinction explains the differences between the total glacier area measurement uncertainties and the changed area measurements reported below.

We have followed Krumwiede et al. (2014) and adapted their approach to our analysis of the different uncertainties of measured snout area and changes in area. The digitized glacier boundaries may be systematically too wide or too narrow, thus the systematic error of glacier area, A_{er}, may be assessed as a percentage of digitized glacier area, A_{gl}, as:

$$A_{er} = \pm 100\,\% \cdot (f_s \cdot n \cdot m)/A_{gl} \quad (1)$$

where, A_{er} = error of glacier area, A_{gl} is digitized glacier area, n is the number of pixels defining the perimeter of the glacier, m = spatial resolution of the image expressed as area of a pixel (e.g., 900 m^2 for a 30 m × 30 m TM image), f_s is the systematic fractional pixel error (e.g. f_s = 0.5 for half a pixel error).

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Glacier area change over a number of years may be computed from digitizations of the same glacier in two images acquired in different years. If the same human operator or same machine algorithm was used and the datasets are similar, the systematic errors may be similar in the two images, so random errors may dominate instead, and then the error in the snout's area change computation, $A_{\text{ch, er}}$ is calculated as:

$$A_{\text{ch, er}} = \pm 100\,\% \cdot (2/j)^{1/2} \cdot (f_r \cdot n_p \cdot m)/A_{\text{gl}}, \tag{2}$$

where j = the number of manual vertices of the vectorized polygon, n_p is the modified perimeter of the snout area, and f_r now is the random pixel error, perhaps still around 0.5. Hence, the random error is far less than the possible systematic error, meaning that we may know the area change much better than we know the total area, as mentioned. This is a key in our measurement and analysis approach and relies on an assumption that glacier area change is concentrated mainly near the snout.

4 Findings

The results presented here account for 607 glaciers belonging to Shashghan, Shigar, Nubra and part of Shyok sub-basins of Karakoram region (Fig. 1). Summarized statistics of the study are shown in Table 2. Uncertainties were calculated according to Eq. (1) (total area) and Eq. (2) (change in area), as detailed in the Supplement. Area-change results are summarized here.

1977–1990: the total area of glaciers was mapped as 7895 km^2 (±8 %) in 1977 which reduced insignificantly to 7885 km^2 (±3 %) by 1990 (nominally −10 km^2, i.e., within uncertainty of no change or allowing either shrinkage or growth by 860 km^2, i.e., roughly 11 % shrinkage to 11 % growth). However, taking the approach described above where we assess the *precision* of measurements for advancing glaciers and retreating glaciers (taken separately), the total areas (and uncertainties) of deglaciation and advancement of these classes of glaciers were 13.6 km^2 (±6 %) and 3.6 km^2 (± 10 %), respectively. See the Supplement for further details on the calculations.

1990–2000: the total mapped area of glaciers had shrunk a little more and became 7882 km^2 (±3 %) up to year 2000 (nominally −3 km^2). The total loss in area of retreating glaciers was 23 km^2 (± 1.5 %), whereas the increased area of advancing glaciers was 20.2 km^2 (±1.8 %) for the monitoring period of 1990–2000.

2000–2010: glacier area has increased to 7885.8 km^2 (±3 %) and 7888.6 km^2 (±3 %) by 2010 and 2013 respectively. In the period of 2000–2010, the total areas of deglaciation and advancement nominally were 7.04 km^2 (±2.8 %) and 10.6 km^2 (± 2.1 %), respectively.

2010–2013: surprisingly, some glaciers also have shown significant change within a short span of three years (2010–2013): nominally 2.7 km^2 (±4 %) and 5.5 km^2 (±3.6 %) of glacial loss and advancement, respectively.

The overall observations indicate that the trends are not of continuous increase or decrease, and that for each period the net change in total glacier area was always of small magnitude, even though some individual glaciers had much larger percentage area changes than the net percentage change of all glaciers combined. The total change in glacier area was due to retreating glaciers during two initial decades, whereas in the later period advancing glaciers caused an increase in total area (Fig. 2). This change in total glacier area was estimated for four time intervals as −9.9 km^2 (1977–1990), −2.8 km^2 (1990–2000), 3.6 km^2 (2000–2010) and 2.8 km^2 (2010–2013).

Discounting the 1977 measurement, which has a large uncertainty, the measured net area change from 1990 to 2013 of all glaciers combined is just about +4 km^2, i.e., not much different from no change at all. Hence, there could have been growth or shrinkage amounting to an annual average rate of anywhere from ±0.0019 % $year^{-1}$ for the 23 year span between these measurements. During the briefer periods within this span there was likewise no significant measureable change in total area. It does not mean that in aggregate the glaciers were completely stable, but the measurements rule out very large changes comparable to the percentage area changes found in many other parts of the Himalaya and around the world (Racoviteanu et al., 2014b; Kargel et al., 2014). Furthermore, lack of measureable significant changes in the aggregate area is

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not to say that there were no measureable changes amongst individual glaciers, as we have documented many advancing and many shrinking glaciers, as well as a larger number of stable glaciers.

These non-uniform changes during 1977 to 1990 were taken as the basis for classifying them into three categories, i.e., advance, retreat and no change (stable) on the basis of change in area in snout area (within the ablation zone). Figures 3–5 show histograms of change in glacier area for three categories during 1977–2013. Among 607 glaciers, only 23 glaciers experienced significant measureable advance during the monitoring period of 1977–1990 (Fig. 6). The total area of these glaciers was 402.5 km^2 in 1977 and had shown increase of about 4 km^2 in 1990. After 1990, these have remained nearly stable up to 2010. In 2013 there was a slight gain in total area of the advancing glaciers up to 407.5 km^2. However, 3 glaciers have continuously advanced up to year 2010 and then became stable in 2013. Seventy nine glaciers were observed retreating during 1977–1990 (Fig. 2). The total area of these glaciers was 2356.3 km^2 in 1977, which showed a reduction of approximately 14 km^2 up to 1990. These shrinking glaciers have shown gradual increase from 1990 to 2013. Moreover, six glaciers out of 79 have experienced continuous retreat up to 2010 and then have become stable.

505 glaciers experienced no measurable change during the period of 1977–1990 (Fig. 6). The total area covered by the 505 glaciers was 5136.2 km^2 in 1977. During the period of 1990 to 2000, the total area of glaciated region decreased to 5126.8 km^2. Then it again increased up to year 2010 with an area of 5129 km^2 and became stable by 2013. 341 glaciers (out of 505 glaciers) have continuously remained stable up to 2013 whereas remaining glaciers have not shown any significant or continuous pattern of retreat, advance or stability.

These results prove that more glaciers (83 glaciers) have advanced substantially in the earlier decade (1990–2000) than in 21st century (41 glaciers). Similarly, the change in glacier area in context of gain or loss or stability also shows the same results, although the total change in area is very small. Interpreting the total results it is observed that the largest fraction of glaciers have remained stable since 1977, which is almost 44 % of total glaciers. The rest of the glaciers have not shown continuous pattern of retreat or advance since 1977. However, the aggregate glacier area, as mentioned before, has not changed dramatically, because stable glaciers dominate in each period and those glaciers that were advancing or retreating have partly balanced each other, and these dynamic glaciers have tended to fluctuate between advance, retreat, and stable conditions at various intervals.

We have tried to show spatial distribution of advance retreat and stability of glaciers. Spatial distribution of advance, retreat and no change in the period of 1977–1990, 1990–2000 and 2000–2013 time intervals in the study area has been shown in Figs. 7–9 respectively. For detailed information about spatial distribution of advance, retreat and no change glaciers, the data have been displayed at smaller scale (basin by basin) in Figs. 10–12. Basically, Shashghan, Shigar, Nubra and part of Shyok basins have been isolated for further study. Thus, the detailed distribution of change in glaciers area of Shashghan basin has been represented in Fig. 10, for Shigar it is in Fig. 11, and Nubra-Shyok basin is represented in Fig. 12.

The spatial distribution of advance, retreat and stability of all glaciers of the study area during three time intervals (1977–1990, 1990–2001, 2001–2013) is shown in Fig. 13. Each glacier is identified with advance or retreat or no change in three time intervals. Glaciers located at north-western and southeastern parts of the study area show tremendous variation in the glaciation and deglaciation for three time frames. Glaciers behaved very differently in each time frame, thus, no significant generalized trend was identified in changes of glaciers. In a few cases, glaciers have experienced advancement and overrode on other glacier and then gradually merged to form a main trunk glacier at a later stage (Fig. 14). In other cases, glaciers were advancing slowly and then stabilized (Fig. 15). In a few cases, the tributary glaciers advanced and merged into main trunk glaciers, whereas the snout of main trunk glacier did not show any considerable change (Fig. 16). The glaciers were monitored annually for the period of 2001–2013 depending on the availability of suitable data. Out of many glaciers, ten glaciers were observed with extraordinary variations for 13 years. This observation is significant in terms of identifying glaciers characterized by a "surge-waste cycle" because of the abrupt advances. Moreover, there are many glaciers showing rapid retreat as well. The high level of variation was identified in these ten glaciers (Fig. 17), e.g. glaciers which have remained stable for 8 years then experienced advancement of 0.4 km^2 then again retreat and then again advancement of 0.8 km^2.

5 Discussion

From the results presented above it emerges that we can classify glaciers in two categories from these set of data: "normal" glaciers and "surge-type" glaciers, as many other regions of temperate glaciers in other parts of the world have. A third category of glaciers undergoing speedy calving-induced retreat – common in the central and eastern Himalaya – is not a major presence in the Karakoram where there are few large lakes.

"Normal" glaciers show a normal (modest) advance or retreat or stability in area, with advances or retreats commonly measured in single digits of meters per year. These glaciers may be stable in mass balance and maintain a constant condition of internal deformation and basal sliding and thus maintain length and area; more commonly, small variations in long-term mass balance, or changes in glacier dynamics related to basal sliding or small rock falls onto the glacier may result in small advances and retreats, with the average condition commonly approaching stability. Other normal glaciers may have low rates of sustained retreat or advance if they have sustained negative or positive mass balance, but if local microclimate conditions or other forcing such as from rockfalls or supraglacial landslides giving rise to these negative or positive balances are themselves balanced (no regional climate trend), then these imbalanced "normal" glaciers may have their net area changes come close to a regional balanced state.

In regions where mass balance has shifted to be negative, the aggregate of glaciers may show a mean slow shrinkage, with individual glaciers showing variable responses

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but more showing slow retreat than slow growth. Or if regional mass balance shifts to positive, more glaciers may show slow growth than slow retreat, but there will be a distribution.

In the second category are those glaciers showing abnormal advance or retreat of snouts. Anomalous advances (surges) are commonly identified due to the presence of features such as looped medial moraines, intense folding visible at the surface, rapid terminus advance, heavy surface crevassing, and high surface velocities. Sharply increased mass balance and episodes of accelerated basal sliding commonly due to large amounts of melt water penetrating to the bed may be primary causes of surging. Commonly, a glacier that has undergone a surge episode will then stabilize briefly and then retreat rapidly over a longer period of time than the surge phase. However, surge and waste phases of a surge-type glacier are not symmetric in duration or rates of advance and recession (advance phases being briefer and faster than retreat phases of the cycle). For the surge-type subpopulation of glaciers there will be an imbalance of fewer advancing glaciers relative to more retreating glaciers (since the waste phase lasts longer than the surge phase). To further complicate the dynamical picture, surge glaciers that are at an early phase of wastage may thin but not exhibit significant area shrinkage or terminus retreat; thus, some fraction of surge-type glaciers may appear for a time to be stable based on length and area measurements.

Individual glaciers will vary through time between advancing and retreating, with their dynamics controlled both by slight oscillations in climate and by intrinsic dynamics that cause length and area oscillations even absent any climate forcing. Regardless of the fraction of surge-type glaciers, the aggregate area of glaciers may remain almost the same if there exists an overall stable state of the population, despite the fact that a large proportion of glaciers are in continual dynamic oscillation. Short-term departures from a balanced state may appear if one or two very large glaciers suddenly surge, but the bigger picture will show balance.

To a first order, this hypothetical situation seems to describe the Karakoram glacier record. The Karakoram exhibits a roughly stable population of dynamic glaciers, ac-

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cording to our analysis of glacier area changes. An overall rough approach toward long-term stability of the whole glacier population in the broader region we surveyed is in sharp distinction with some other areas of the nearby Himalaya and most parts of the glacierized world. Thus, we have added many new details, particularly in the temporal domain, to the concept of the Karakoram Anomaly first identified by Hewitt (2005).

An inventory carried out by Bhambri et al. (2013) in Shyok Valley is significant in terms of dynamics of glaciers since 1973; a small fraction of glaciers were identified as surging in the Upper Shyok Valley, supporting our finding as well.

Do our new results imply that the climate in the Karakoram is in a long-term stable condition? Not necessarily. If increases in snow precipitation take place with an increase in temperature, there are some situations that may cause a nearly balanced state of the population of glaciers. Hence, a stable population of glaciers may signify either long-term unchanging climate, or it may signify that various dynamic climatic parameters are balancing each other. Measurements of ice throughout (changes of which may be indicated by surface velocity flow fields, or by direct field measurements of seasonal accumulation and ablation) would discriminate which of these climate scenarios applies.

6 Conclusion

The glaciers in our study area of the Karakoram include many advancing glaciers and many retreating ones, but most of the glaciers have remained nearly stable over several decades. A couple percent of the glaciers are surge types. There have been temporal changes in aggregate glacier behavior. Before 1990 the glaciers on average were either stable or retreating. In the last two decades Karakoram glaciers, on average, have experienced noticeable advances of their snouts and areas. The aggregate changes, however, are small for every period considered. There is a significant finding that it is mainly tributary glaciers which show advancement or retreat; there are exceptions of main trunk glaciers showing retreat or advance. It is emphasized in this article that

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it is not only abnormal advancement but sometimes abnormal retreat that is also observed. Although the population of glaciers is dynamic in time and geographically, we find that largely the population is almost stable but includes dynamics disturbances due to surge-waste cycles of a minority of the glaciers and smaller fluctuations of many other glaciers.

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References

Bahuguna, I. M., Rathore, B. P., Brahmbhatt, R. M., Sharma, M., Sunil Dhar, Randhawa, S. S., Kireet Kumar, Rhomshoo, S., Shah, R. D., Ganjoo, R. K., and Ajai: Are the Himalayan glaciers retreating?, Curr. Sci. India, 106, 1008–1013, 2014.

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., and Chevallier, P.: Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), Remote Sens. Environ., 108, 327–338, 2007.

Bhambri, R., Bolch, T., Chaujar, R. K., and Kulshreshtha, S. C.: Glacier changes in the Garhwal Himalayas, India 1968–2006 based on remote sensing, J. Glaciol., 97, 543–556, 2011.
Bhambri, R., Bolch, T., and Chaujar, R.: Frontal recession of Gangotri glacier Garhwal Himalayas, from 1965 to 2006, measured through high resolution remote sensing data, Curr. Sci. India, 102, 489–494, 2012.
Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D. P., Srivastava, D., and Pratap, B.: Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram, The Cryosphere, 7, 1385–1398, doi:10.5194/tc-7-1385-2013, 2013.
Bolch, T., Pieczonka, T., and Benn, D. I.: Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery, The Cryosphere, 5, 349–358, doi:10.5194/tc-5-349-2011, 2011.
Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M.: The state and fate of Himalayan glaciers, Science, 336, 310–314, 2012.
Brahmbhatt, R. M., Bahuguna, I. M., Rathore, B. P., Kulkarni, A. V., Nainwal, H. C., Shah, R. D., and Ajai: A comparative study of deglaciation in two neighboring basins (Warwan and Bhut) of Western Himalaya, Curr. Sci. India, 103, 298–304, 2012.
Cazenave, A. and Chen, J.: Time-variable gravity from space and present-day mass redistribution in the Earth system, Earth Planet. Sc. Lett., 298, 263–274, doi:10.1016/j.epsl.2010.07.035, 2010.
Cogley, J. G., Kargel, J. S., Kaser, G., and van der Veen, C. J.: Tracking the source of glacier misinformation, Science, 326, 924–925, 2010.
Copland, L., Sylvestre, T., Bishop, M. P., Shroder, J. F., Seong, Y. B., Owen, L. A., Bush, A., and Kamp, U.: Expanded and recently increased glacier surging in the Karakoram, Arct. Antarct. Alp. Res., 43, 503–516, 2011.
Dobhal, D. P., Gergan, J. T., and Thayyen, R. J.: Mass balance studies of the Dokriani glacier from 1992 to 2000, Garhwal Himalaya, India, Bull. Glaciol. Res., 25, 9–17, 2008.
Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers, P. Natl. Acad. Sci. USA, 108, 14011–14014, doi:10.1073/pnas.1106242108, 2011.
Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain ofKarakoram glaciers in the early 21st century, Nat. Geosci., 5, 322–325, 2012.

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9, 1555–1592, 2015

Satellite monitoring of glaciers in the Karakoram from 1977 to 2013

R. M. Brahmbhatt et al.

Gardelle, J., Berthier, E., Arnaud, Y., and Kääb, A.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, The Cryosphere, 7, 1263–1286, doi:10.5194/tc-7-1263-2013, 2013.

Hewitt, K.: The Karakoram anomaly? Glacier expansion and the "elevation effect," Karakoram Himalaya, Mt. Res. Dev., 25, 332–340, 2005.

Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 482, 514–518, 2012.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, Nature, 488, 495–498, doi:10.1038/nature11324, 2012.

Kääb, A., Nuth, C., Treichler, D., and Berthier, E.: Brief Communication: Contending estimates of early 21st century glacier mass balance over the Pamir-Karakoram-Himalaya, The Cryosphere Discuss., 8, 5857–5874, doi:10.5194/tcd-8-5857-2014, 2014.

Kargel, J. S., Abrams, M. J., Bishop, M. P., Bush, A., Hamilton, G., Jiskoot, H., Kääb, A., Kieffer, H. H., Lee, E. M., Paul, F., Rau, F., Raup, B., Shroder, J. F., Soltesz, D. L., Stearns, L., and Wessels, R.: Multispectral imaging contributions to global land ice measurements from space, Remote Sens. Environ., 99, 187–219, 2005.

Kargel, J. S., Cogley, J. G., Leonard, G. J., Haritashya, U., and Byers, A.: Himalayan glaciers: the big picture is a montage, P. Natl. Acad. Sci. USA, 108, 14709–14710, 2011.

Kargel, J. S., Leonard, G. J., Bishop, M. P., Kaab, A., and Raup, B. (Eds.): Global Land Ice Measurements from Space, Springer-Praxis, Heidelberg, ISBN 978-3-540-79817-0, e-ISBN 978-3-540-79818-7, doi:10.1007/978-3-540-79818-7, 2014.

Krumwiede, B. S., Kamp, U., Leonard, G. J., Dashtseren, A., Walther, M., and Kargel, J. S.: Recent glacier changes in the Mongolian Altai Mountains: case studies from Tavan Bogd and Munkh Khairkhan, Chapter 22, in: Global Land Ice Measurements from Space, edited by: Kargel, J. S., Leonard, G. J., Bishop, M. P., Kaab, A., and Raup, B., Springer-Praxis, Heidelberg, 481–508, ISBN 978-3-540-79817-0, e-ISBN 978-3-540-79818-7, 2014.

Kulkarni, A. V. and Karyakarte, Y.: Observed changes in Himalayan glaciers, Curr. Sci. India, 106, 237–244, 2014.

Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood. R. K., and Dhar, S.: Glacial retreat in Himalayas using Indian Remote Sensing satellite data, Curr. Sci. India, 92, 69–74, 2007.

Matsuo, K. and Heki, K.: Time-variable ice loss in Asian high mountains from satellite gravimetry, Earth Planet. Sc. Lett., 290, 30–36, 2010.
Mayer, C., Lambrecht, A., Belo, M., Smiraglia, C., and Diolaiuti, G.: Glaciological characteristics of the ablation zone of Baltoro Glacier, Karakorum, Ann. Glaciol., 43, 123–131, 2006.
Mayer, C., Fowler, A. C., Lambrecht, L., and Scharrer, K.: A surge of North Gasherbrum Glacier, Karakoram, China, J. Glaciol., 57, 904–916, 2011.
Minora, U., Bocchiola, D., D'Agata, C., Maragno, D., Mayer, C., Lambrecht, A., Mosconi, B., Vuillermoz, E., Senese, A., Compostella, C., Smiraglia, C., and Diolaiuti, G.: 2001–2010 glacier changes in the Central Karakoram National Park: a contribution to evaluate the magnitude and rate of the "Karakoram anomaly", The Cryosphere Discuss., 7, 2891–2941, doi:10.5194/tcd-7-2891-2013, 2013.
Racoviteanu, A., Arnaud, Y., Williams, M., and Manley, W. F.: Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya, The Cryosphere Discuss., 8, 3949–3998, doi:10.5194/tcd-8-3949-2014, 2014a.
Racoviteanu, A., Bolch, T., Bhambri, R., Bajracharya, S., Mool, P., Chaujar, R. K., Kargel, J., Leonard, G., Furfaro, R., Kääb, A., Rauenfelder, R., Sossna, I., Kamp, U., Byrne, M., Kulkarni, A. V., Baghuna, I. M., Berthier, E., Arnaud, Y., Bishop, M. P., and Shroder, J. F.: Himalayan glaciers (India, Bhutan, Nepal), chapter 24, in: Global Land Ice Measurements from Space, edited by: Kargel, J. S., Leonard, G. J., Bishop, M. P., Kaab, A., and Raup, B., Springer-Praxis, Heidelberg, 549–582, ISBN 978-3-540-79817-0, e-ISBN 978-3-540-79818-7, doi:10.1007/978-3-540-79818-7, 2014b.
Rankl, M., Kienholz, C., and Braun, M.: Glacier changes in the Karakoram region mapped by multimission satellite imagery, The Cryosphere, 8, 977–989, doi:10.5194/tc-8-977-2014, 2014.
Raup, B. H., Andreassen, L., and Bolch, T.: Remote sensing of glaciers (Chapter 7), in: Remote Sensing of the Cryosphere, edited by: Tedesco, M., Wiley, ISBN: 9781118368855, 123–156, 2014
Scherler, D., Bookhagen, B., and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nat. Geosci., 4, 156–159, 2011.
Schmidt, S. and Nusser, M.: Changes of high altitude glaciers from 1969 to 2010 in the Trans-Himalayan Kang Yatze Massif, Ladakh, Northwest Indian, Arct. Antarct. Alp. Res., 44, 107–121, 2012.

TCD
9, 1555–1592, 2015

Satellite monitoring of glaciers in the Karakoram from 1977 to 2013

R. M. Brahmbhatt et al.

Velicogna, I.: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, Geophys. Res. Lett., 36, 1–5, 2009.
Venkatesh, T. N., Kulkarni, A. V., and Srinivasan, J.: Relative effect of slope and equilibrium line altitude on the retreat of Himalayan glaciers, The Cryosphere, 6, 301–311, doi:10.5194/tc-6-301-2012, 2012.
Yuning, F. and Freymueller, J. T.: Seasonal and long-term vertical deformation in the Nepal Himalaya constrained by GPS and GRACE measurements, J. Geophys. Res., 117, B03407, doi:10.1029/2011JB008925, 2012.

Table 1. The list of datasets.

Year	Type	Date
1977/78/79	MSS	9 Mar 1977 18 Jul 1978 2 Aug 1977
1989/90	Landsat TM	(147/36, 148/35) 9 Oct 1989 (148/35, 148/36) 29 Jun 1990
2000/01	Landsat TM	(147/36) 31 Oct 2000 (148/35) 18 May 2001 (148/36) 16 Jul 1999
	LISS III	(94/45) 22 Jul 2001 (94/46) 26 Oct 2001
2000–2009	Landsat ETM+	(148/35) 14 Aug 2004; 7 Dec 2005; 7 Dec 2006; 8 Nov 2006; 23 Aug 2007; 12 Aug 2009; 31 Aug 2010; 27 Jul 2009; 21 May 2008; 26 Sep 2009; 26 Sep 2008 (147/36) 2 Aug 2002; 26 Jun 2006; 26 Aug 2005; 30 Sep 2006; 13 Jun 2007; 16 Aug 2007; 2 Aug 2008; 3 Sep 2008; 6 Sep 2009 (148/36) 2 Sep 2005; 23 Aug 2007; 12 Aug 2008; 28 Aug 2009; 12 Oct 2008; 29 Sep 2009
2010/11	Landsat ETM+	(148/35) 5 Nov 2011 (147/36) 12 Sep 2011
		(94/45) 3 Oct 2010 (94/46) 3 Oct 2010
2013		(147/36) 12 Feb 2013 (147/36) 25 Sep 2013 (147/36) 24 Aug 2013 (148/35) 3 Feb 2013

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Table 2. Overview results of glacier change for 607 glaciers.

Year	Total Glacier Area (km^2)	Period	Change in total glacier area (km^2)	Change of area of advancing glacier (km^2)	Change of area of retreating glaciers (km^2)
1977	7895 (+8 %)	–	–	–	–
1990	7885 (+3 %)	1977–1990	(–)10 (+8 %)	3.62 (+10 %)	13.6 (+6 %)
2000	7882 (+3 %)	1990–2000	(–)3 (+1.7 %)	20.2 (+1.8 %)	23 (+1.5 %)
2010	7885.8 (+3 %)	2000–2010	(+)4 (+2.5 %)	10.6 (+2.1)	7.04 (+2.8 %)
2013	7888.6 (+3 %)	2010–2013	(+)3 (+3.8 %)	5.5 (+3.6)	2.7 (+4 %)

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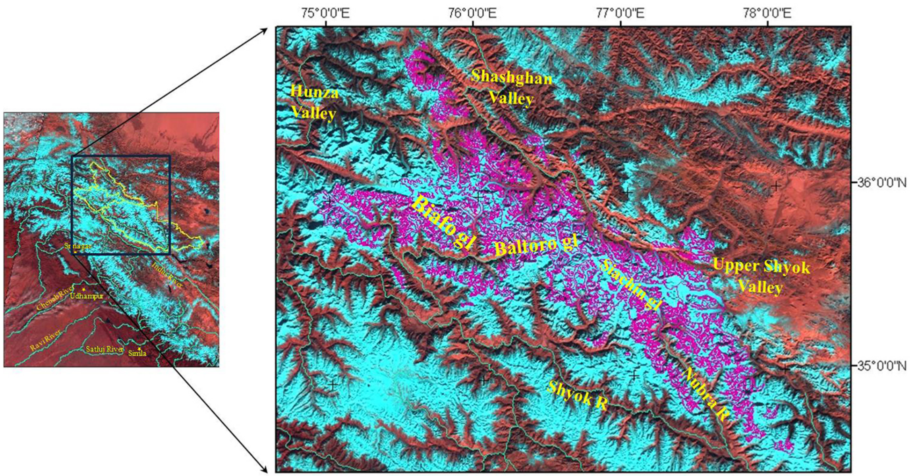

Figure 1. Locations of glaciers monitored in Karakoram region shown in satellite data. (AWiFS image of year 2014 showing FCC of SWIR-NIR-Red.)

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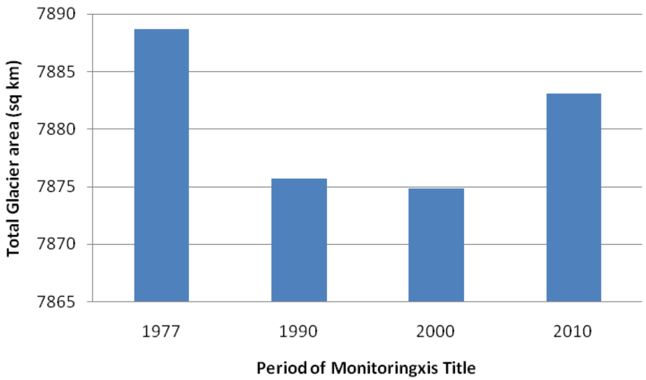

Figure 2. Change in total area of glaciers from 1977 to 2013.

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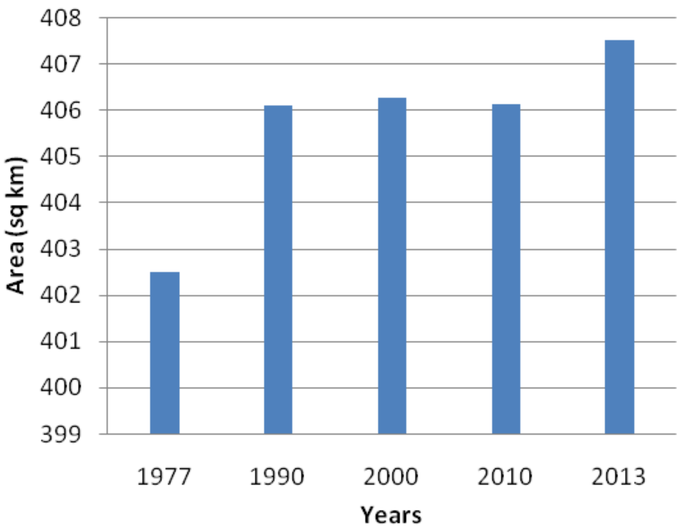

Figure 3. Change in total area of advanced (advancement for the period of 1977–1990) glaciers from 1977 to 2013.

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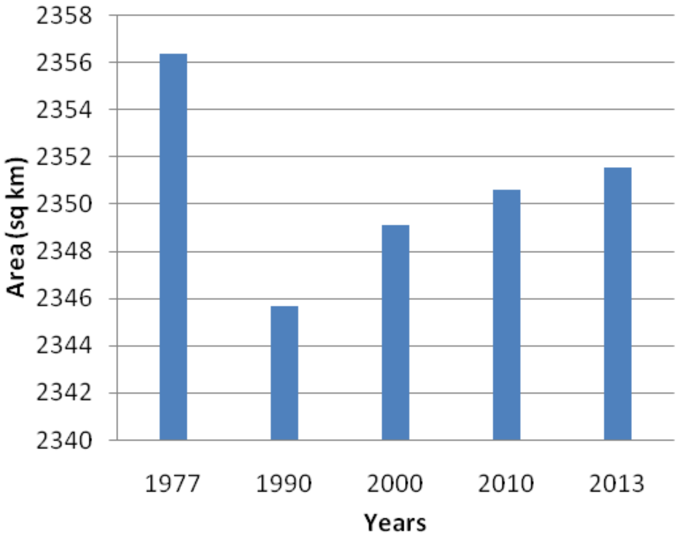

Figure 4. Change in total area of retreated (retreat for the period of 1977–1990) glaciers from 1977 to 2013.

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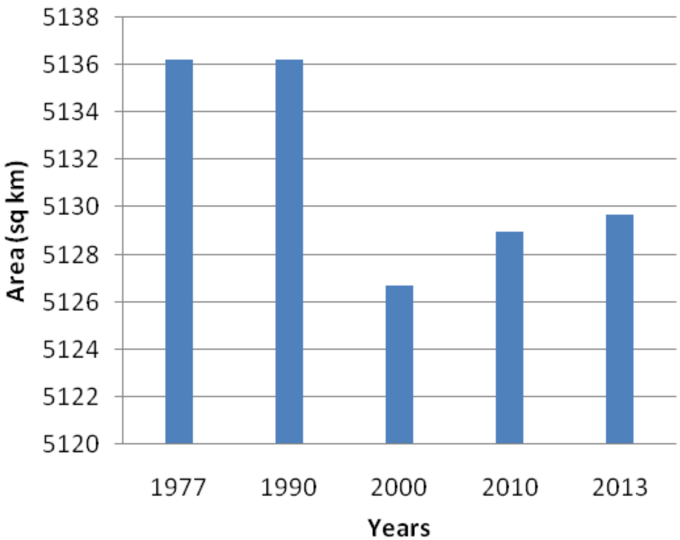

Figure 5. Change in total area of stable (no change for the period of 1977–1990) glaciers from 1977 to 2013.

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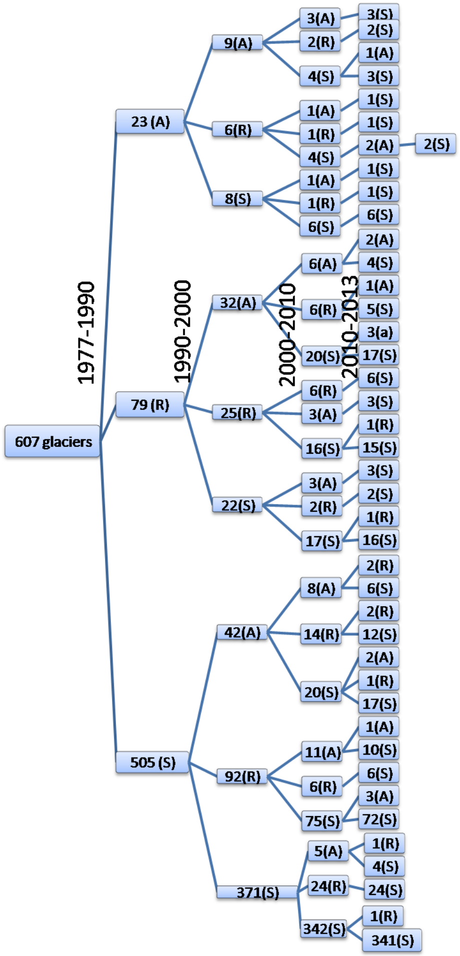

Figure 6. Chart showing the statistics of stable advancing and retreating glaciers from 1977–2013.

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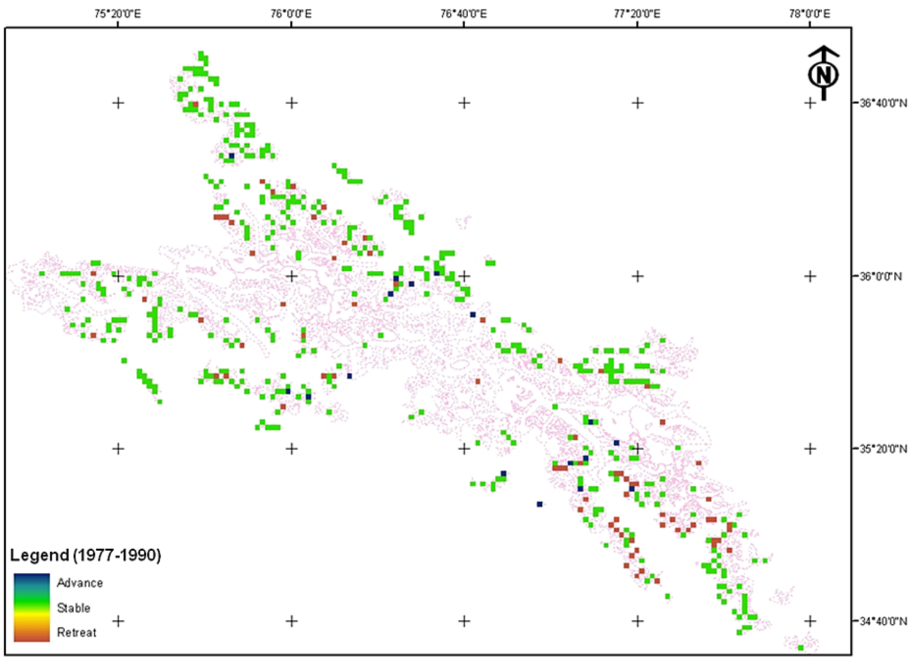

Figure 7. Image showing the glaciers which have experienced the retreat, advance and no change for the period of 1977 to 1990.

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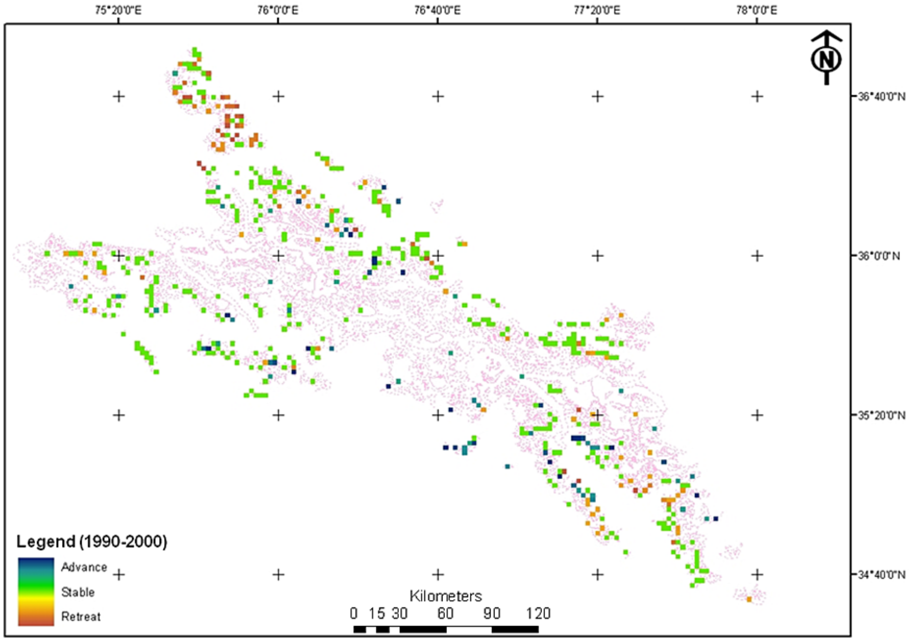

Figure 8. Image showing the glaciers which have experienced the retreat, advance and no change for the period of 1990 to 2000.

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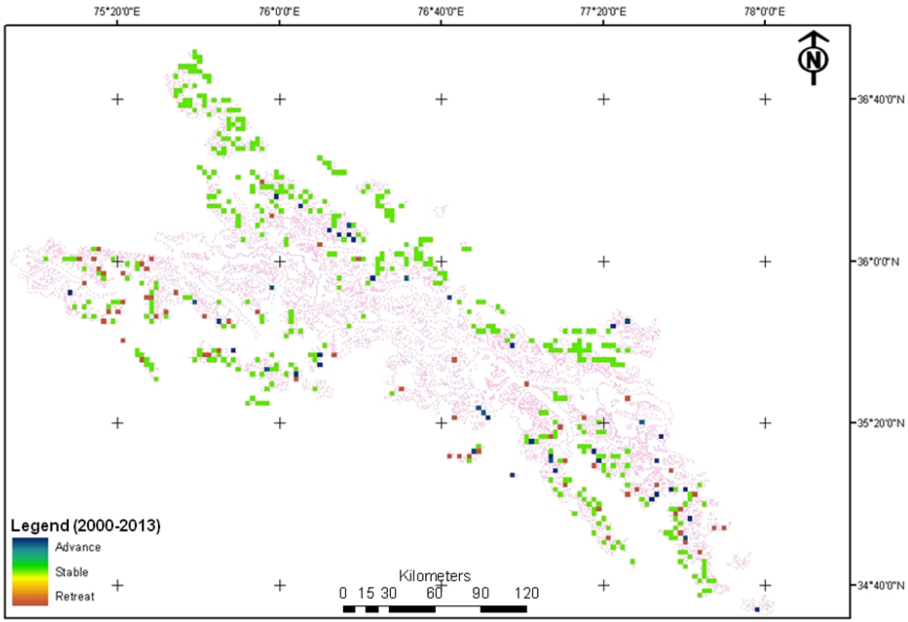

Figure 9. Image showing the glaciers which have experienced the retreat, advance and no change for the period of 2000 to 2013.

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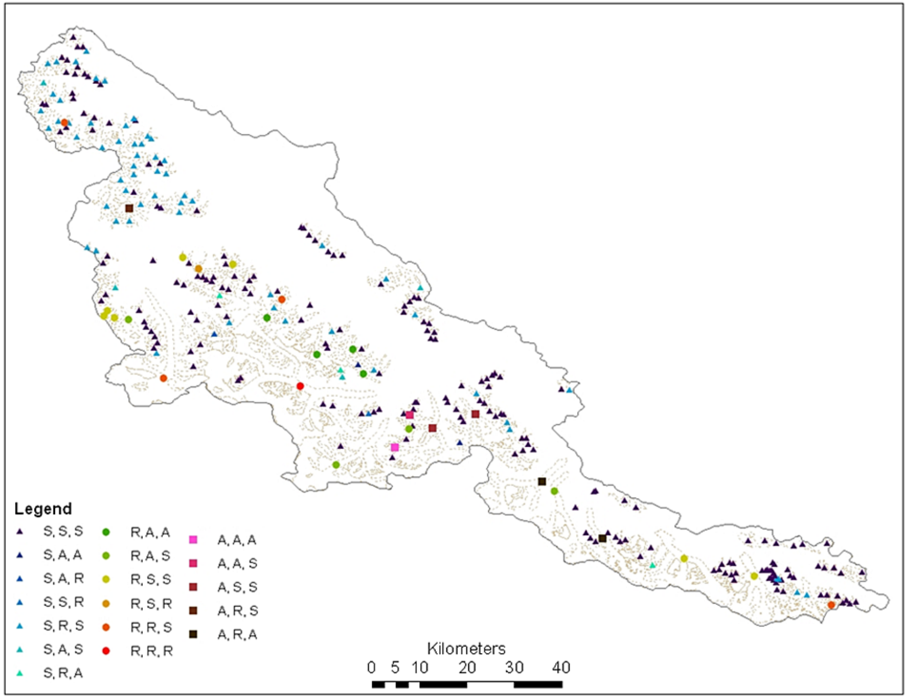

Figure 10. Image showing the overview change of glaciers in Shashghan sub-basin of Karakoram since 1977 to 2013. Note: R = Retreat, A = Advance and S = Stable. R-A-S = Retreat (in 1977–1990) – Advance (in 1990–2000) – Stable (in 2000–2013).

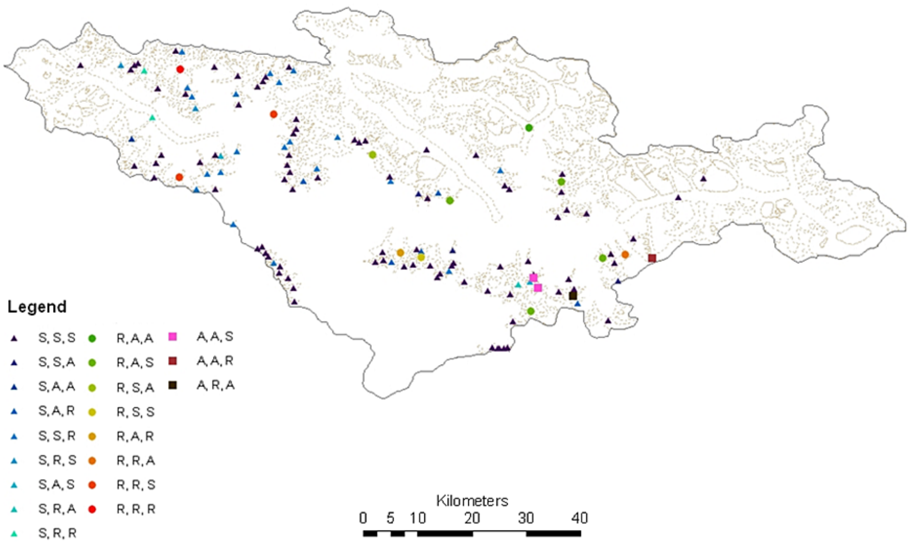

Figure 11. Image showing the overview change of glaciers in Shigar sub-basin of Karakoram since 1977 to 2013. Note: R = Retreat, A = Advance and S = Stable. R-A-S = Retreat (in 1977–1990) – Advance (in 1990–2000) – Stable (in 2000–2013).

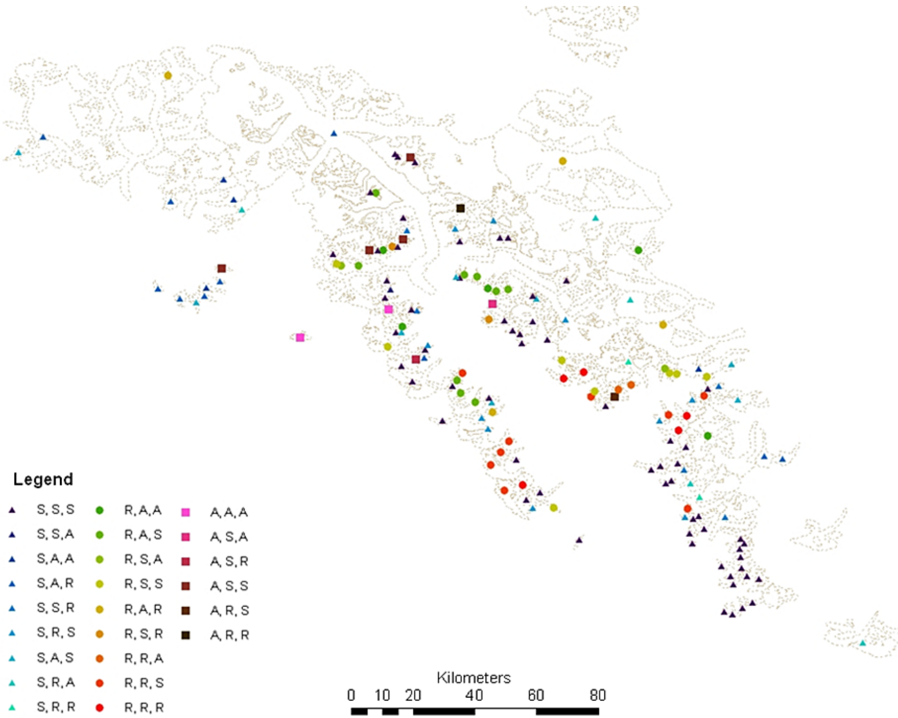

Figure 12. Image showing the overview change of glaciers in Nubra-Shyok sub-basin of Karakoram since 1977 to 2013. Note: R = Retreat, A = Advance and S = Stable. R-A-S = Retreat (in 1977–1990) – Advance (in 1990–2000) – Stable (in 2000–2013).

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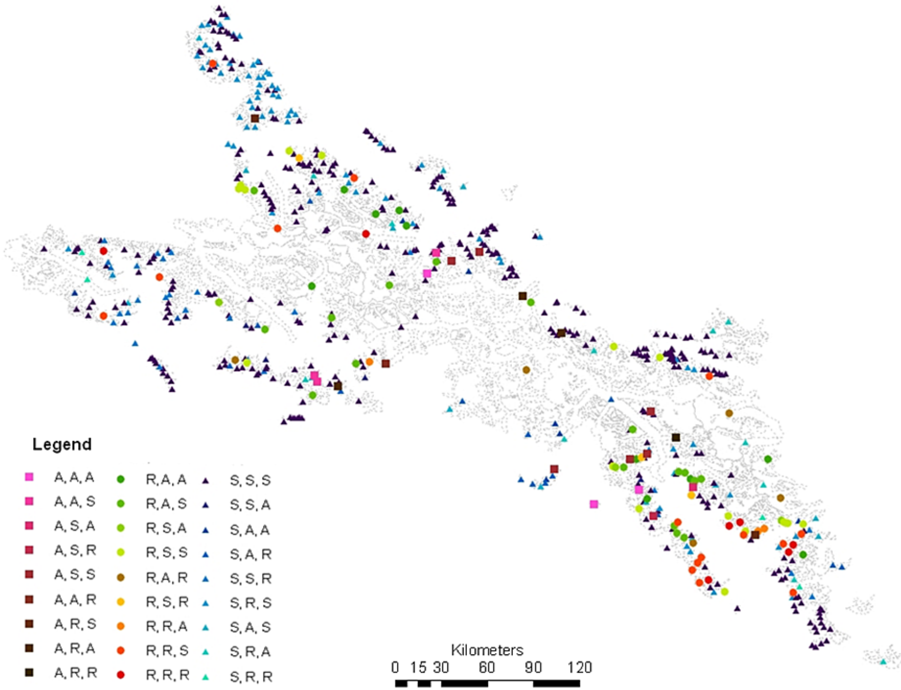

Figure 13. Spatial distribution of change in area of glaciers of Karakoram since 1977. Note: R = Retreat, A = Advance and S = Stable. E.g.: R-A-S = Retreat (in 1977–1990) – Advance (in 1990–2000) – Stable (in 2000–2013).

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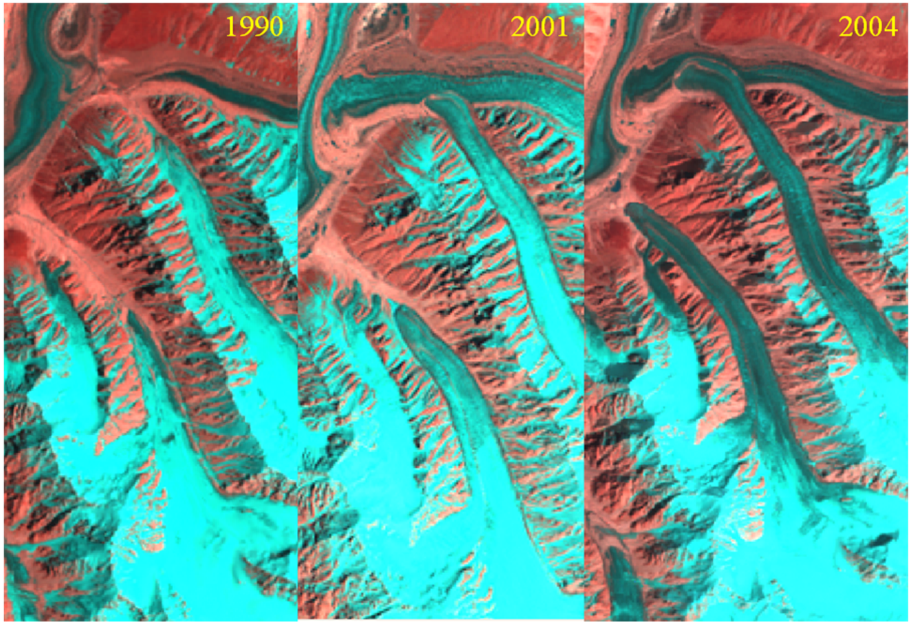

Figure 14. Landsat images of TM (1990), ETM (2001), ETM+ (2004) showing overriding and advancement of tributaries on main glacier (Panmah Glacier) (FCC in SWIR-NIR-Red).

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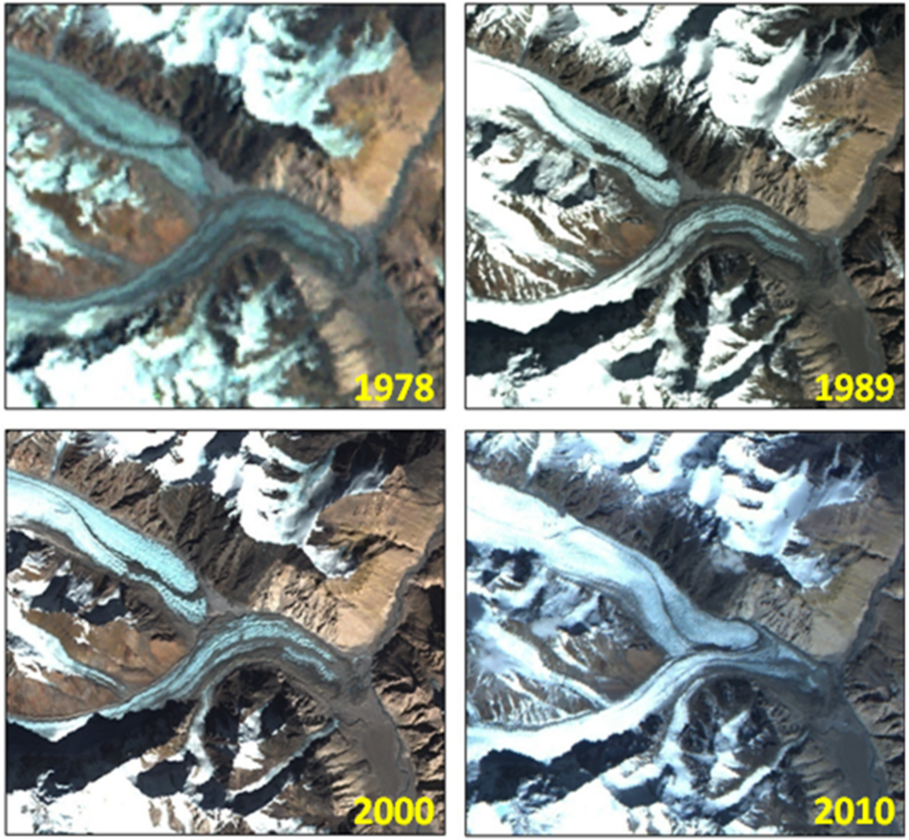

Figure 15. Landsat Images of MSS (1978), TM (1989), ETM (2001), ETM+ (2010) showing overriding and advancement of tributary glaciers (Chong Kumdan) (FCC in SWIR-NIR-Red).

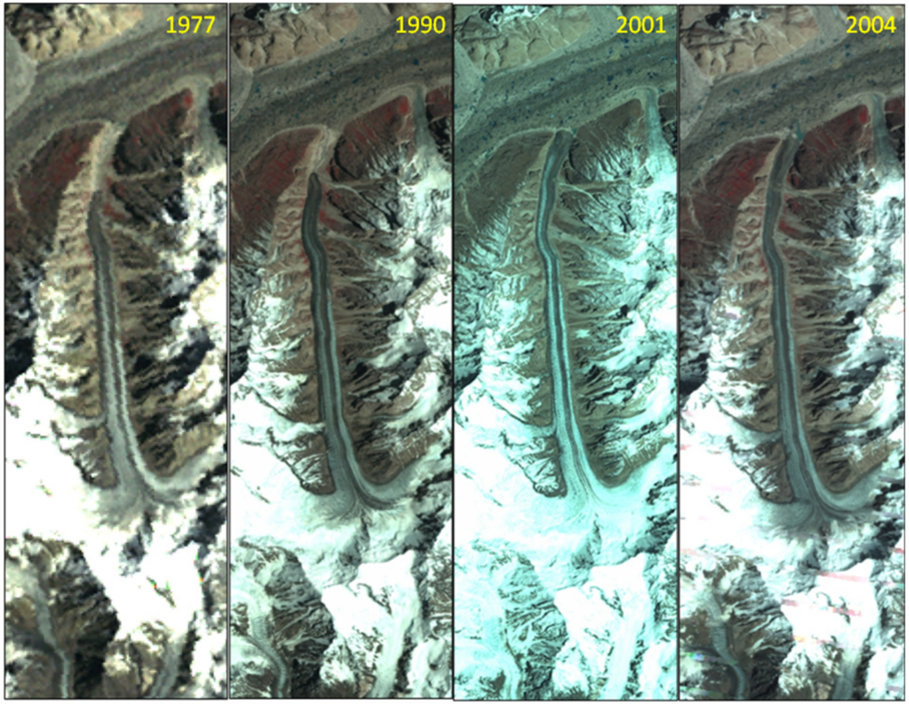

Figure 16. Images showing advancing of tributary glaciers upto bank of main trunk (Baltoro) glaciers.

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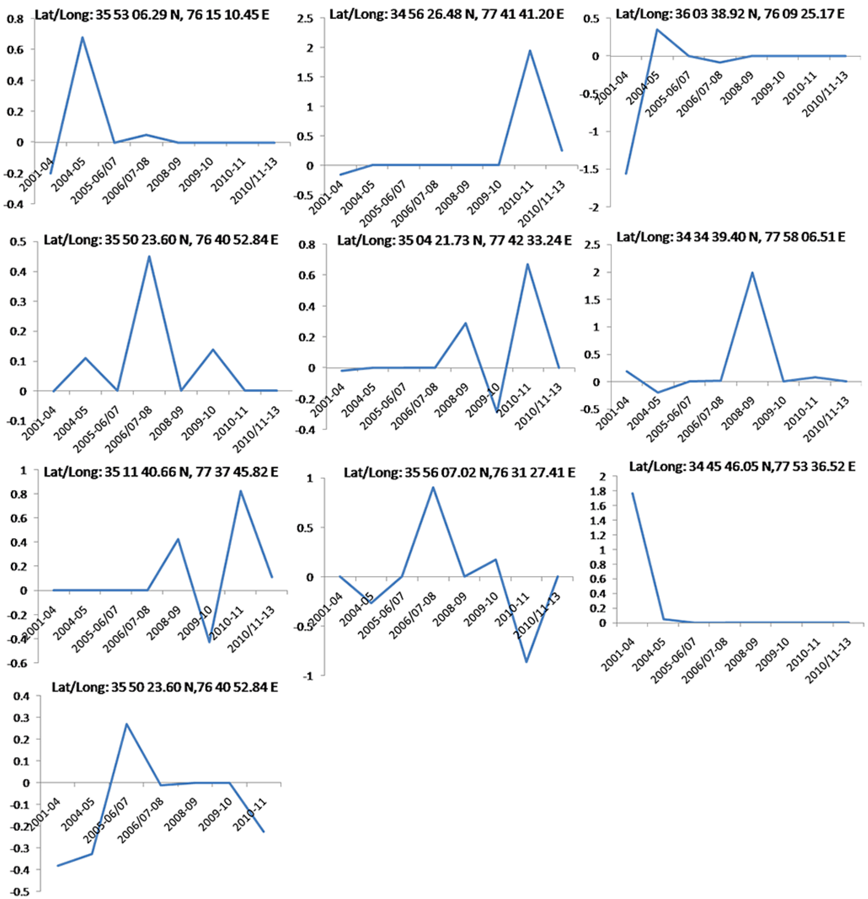

Figure 17. Graphs showing annual changes in area of individual glaciers from 2001 to 2013 (Central Lat/Long of individual glacier is given). The abrupt change in glacier area can be attributed to surging of glaciers in a specific period.

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