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Revealing glacier flow and surge dynamics from animated satellite image sequences: examples from the Karakoram

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Abstract

Although animated images are very popular on the Internet, they have so far found only limited use for glaciological applications. With long time-series of satellite images becoming increasingly available and glaciers being well recognized for their rapid changes and variable flow dynamics, animated sequences of multiple satellite images reveal glacier dynamics in a time-lapse mode, making the otherwise slow changes of glacier movement visible and understandable for a wide public. For this study animated image sequences were created from freely available image quick-looks of orthorectified Landsat scenes for four regions in the central Karakoram mountain range. The animations play automatically in a web-browser and might help to demonstrate glacier flow dynamics for educational purposes. The animations revealed highly complex patterns of glacier flow and surge dynamics over a 15-year time period (1998–2013). In contrast to other regions, surging glaciers in the Karakoram are often small (around 10 km²), steep, debris free, and advance for several years at comparably low annual rates (a few hundred m a⁻¹). The advance periods of individual glaciers are generally out of phase, indicating a limited climatic control on their dynamics. On the other hand, nearly all other glaciers in the region are either stable or slightly advancing, indicating balanced or even positive mass budgets over the past few years to decades.

1 Introduction

Analysis of sequential satellite images has become a common tool for deriving glacier changes through time in all parts of the world. A “standard” way of documenting these changes in scientific journals is the overlay of glacier outlines from different points in time on one of the images used for the analysis (e.g. Baumann et al., 2009; Bham-bri et al., 2014; Paul et al., 2004). In the case of multiple images being available and changes mostly taking place at the glacier terminus (e.g. during an advance or retreat phase), terminus positions are indicated by multiple lines with years either attached to

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them (e.g. Jiskot and Juhlin, 2009) or colour coded (McNabb and Hock, 2014; Quincey et al., 2011; Rankl et al., 2014). In case of complex interactions taking place between two glaciers (e.g. a tributary is merging with another glacier or a surge is resulting in looped moraines), phases of the changes are illustrated showing sequential images side-by-side (e.g. Belò et al., 2008; Bhambri et al., 2013; Copland et al., 2011; Mukhopadhyay and Khan, 2014) or by two-dimensional drawings of changes in major moraine patterns (e.g. Hewitt, 2007; Meier and Post, 1969).

Although these representations of changing glaciers are scientifically sound and exact, they have some limitations in demonstrating what is going on. The key issue is related to the limited ability of the human brain to recognize differences between two (static) images when shown side-by-side or to translate various outlines of terminus positions into the correct sequence of changes, in particular when they are out of phase for a couple of glaciers. On the other hand, the human brain recognizes movement well and tends to compensate missing parts in a sequence of animated images due to the slow processing of visual information, also known as the “phi-phenomenon” (e.g. MacGillivray, 2007). This also helps in translating time-lapse photography into continuous motion thus making the dynamic nature of otherwise slowly moving objects or natural phenomena visible (e.g. cloud development, aurora, tides). While cameras with an interval timer were not common a decade ago and related footage was rare, today’s widespread availability of webcams allows pictures to be taken remotely and automatically each day (or any period) at regular intervals. This could be particularly interesting when glaciers are imaged, as their movement is normally much too slow to be recognized (e.g. www.chasingice.com).

At the satellite scale, the application of “flicker” images (basically a rapid alternation of at least two images taken a few years apart) for demonstrating glacier changes is common practice these days and has been used to analyse glacier motion (Kääb et al., 2003). In this way, coherent patterns of displacement of the glacier surface have long been used to determine surface flow velocities from feature tracking using cross-correlation or other techniques (e.g. Kääb and Vollmer, 2000; Scambos et al., 1992).

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With the now free availability of long time-series (starting in 1984) of orthorectified satellite imagery from Landsat (e.g. Wulder et al., 2012), it is possible to combine sequential satellite images into longer sequences (> 10 years) and demonstrate glacier flow and dynamic changes over large regions. This provides new insights into such phenomena as the mutual interaction of different glaciers, fast and slow flow of different glacier segments, advance and retreat patterns, surge characteristics, down-wasting, and the dynamics of supra and pro-glacial lakes. Depending on the time step between the original images and the velocity of the glaciers, the impression of more or less continuous flow can be obtained by animating the individual images at high speed.

One of the most fascinating regions for such an application is the Karakoram mountain range with its many surging glaciers (e.g. Copland et al., 2011; Gardelle et al., 2013; Hewitt, 2007; Rankl et al., 2014). According to Jiskoot (2011), a surging glacier oscillates between a period of slow or normal flow (for tens to hundreds of years) and an active or surge phase with flow velocities being increased by a factor of 10 to 1000 over a shorter period (a few months to years) that sometimes results in marked frontal advances (km scale). All three components (time periods for both phases, velocities, terminus advance) reportedly vary over a wide range, resulting in an unclear separation from non-surge-type glaciers that might, for example, just advance over an extended period of time (Meier and Post, 1969). The surge-type behaviour often becomes evident from distortions of the normally parallel alignment of medial and/or lateral moraines. Such distortions may result from the speed-up of either a specific section of a glacier or the merging of a surging tributary with the main glacier.

With this study the power of animated sequences of orthorectified satellite images is demonstrated by revealing the laminar flow of non-surge-type glaciers, the different flow patterns of surge-type glaciers, and how lakes and debris patterns on the glacier surface change through time, among others. Though this might be seen as a less quantitative approach than that of studies determining the exact rates of glacier change, the information obtained by looking at high-speed animations of the individual images can provide additional insight into glacier behaviour. There is also potential for using such

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animations for educational purposes, basically for everybody interested in seeing how glaciers flow and how glaciers are changing through time. The animations use the very old (> 25 years) image format GIF, which has its drawbacks in terms of the number of colours that can be used (only 256), but to my knowledge it is the only format that allows a looping of high-frequency animations with screen-size images. The format has recently becoming increasingly popular on the Internet (e.g. giphy.com) for short repetitive animations due to its easy use (no special software required) and relatively small file size.

Details of image processing are described below, followed by a discussion of what the animations reveal about glacier and landscape dynamics in four selected regions in the central Karakoram. The discussion provides some initial perspectives on the interpretation of the changes.

2 Study region, data sets and methods

The study region is located in the central Karakoram mountain range to the north of and including the large and well-studied Baltoro Glacier (Fig. 1). Four regions are selected for the animations: (1) Baltoro, (2) Panmah, (3) Skamri/Sarpo Laggo, and (4) Shaks-gam. All regions are well known for their many surging glaciers (for an overview see Copland et al., 2011 or Rankl et al., 2014) of which several have been studied in more detail (Diolaiuti et al., 2003; Hewitt, 2007; Quincey et al., 2011; Rankl et al., 2014). The region is characterized by very steep and high terrain (often reaching more than 7000 m a.s.l.) with numerous multi-basin valley glaciers, that often have further tributary glaciers in the ablation region (Iturrizaga, 2011). Several valley glaciers in this region exhibit extended periods (> 10 years) of strong advance and/or fast flow (Rankl et al., 2014). The anomalous glacier behaviour in the study region (mass gain and advancing glaciers over the past two decades) relative to most other regions of the world has been named the “Karakoram Anomaly” (e.g. Bolch et al., 2012; Hewitt, 2005). This might be attributable to an increase in precipitation (e.g. Janes and Bush, 2012), but the large

number of surging glaciers in the region might have a non-climatic explanation (e.g. Hewitt, 2005; Jiskoot, 2011). Further details about the topo-climatic characteristics of the region can be found in Hewitt (2014).

The region is completely covered by Landsat scene 148-35 (path-row) and partly also by scene 149-35 (Fig. 1). Useful Landsat scenes (sensors TM, ETM+ and OLI) acquired near the end of the ablation period (end of summer) are available for ten individual years since 1998 and one scene from 1991 (see Table 1). A Landsat MSS scene (path-row: 160-35) from August 1977 was used to provide information on previous glacier extents, but is not integrated in the animations. The scene from 1991 was only used for the Baltoro sub-region. Only the orthorectified quick-looks of all scenes were downloaded from earthexplorer.usgs.gov and used for the animations. They are provided as false colour composites at the original 30 m resolution showing glaciers in light blue to cyan, clouds in white, water in dark blue, and bare terrain in pink to purple. All scenes are processed in a standardized way at USGS (with colours balanced) and are provided with several extra files listing projection information and geolocation for easy import into GIS software. Most images have too much snow cover to allow creation of glacier outlines for an inventory.

The animations are created by displaying all images in GIS software (e.g. QGIS, ArcMap), exporting the maps to a 24 bit image file, converting all images to gif format with xv (that has to my knowledge the best conversion of the 24 bit colour space to 8 bit), and creation of the animated gif image with a delay of 1/10 s using *convert* from ImageMagick. Annotated versions of the four sub-regions are shown in Figs. 2 to 5 for orientation and as a reference (using the 2004 scene). In general, the temporal difference between two images in the animation is two years, but sometimes (depending on cloud conditions) it is three or even more. The respective scenes used are marked in Table 1 for each of the four regions. The animations can be viewed and downloaded as Supplement.

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3 Results

3.1 Terminus fluctuations

A wide range of dynamic changes is visible in the animations. In sub-region (1) covering Baltoro Glacier and its numerous tributaries (Fig. 2), nearly all glaciers show laminar flow. Despite the well recognizable high velocity of the main glacier, its terminus remains in about the same position and supra-glacial lakes on the surface come and go. There are two surge-type glaciers in the north and one in the south (Liligo), but they are too small to leave an impact on the main glacier in terms of deformed moraines. Four rather small glaciers in the south-west corner of the image (south of the Baltoro terminus) show a mixture of surging and rapid advance that has not been mentioned in previous studies.

In the Panmah region (Fig. 3, sub-region 2), the most obvious features of the animation are the variability in late summer snow extent, and the differences between the behaviour of normal vs. fast-flowing (or surging) glaciers. While the larger tongues of Biafo, Choktoi and Nobande Sobonde (NS) glaciers show the laminar flow of non-surge-type glaciers, several (partly tributary) glaciers show unsteady fast flow (i.e. active surging), partly colliding with other glaciers and creating the well-known distorted and looped moraines (see also Hewitt, 2007). The termini of many of the much smaller surrounding glaciers are either stationary or slowly advancing, i.e. in terms of past mass budgets they seem to be healthy. Also visible is the asynchronous nature of the advance/retreat (or down-wasting) phases. While some glaciers had just finished their surge (before 1998), others started to surge (1st Feriole), were already in full surge mode (e.g. Shingchukpi) or began to surge later (e.g. in 2006 for Drenmang). It is also noteworthy that even fluctuations of glacier tongues with a width of only one or two pixels at the terminus can easily be followed in the animation, also helping in identifying their terminus positions.

The variability described above for sub-region (2) is also apparent in sub-regions (3) and (4) depicted in Figs. 4 and 5. While some glaciers are in full surge or started

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surging after the year 2000, others just finished their surge and showed the characteristic down-wasting with a separation of the lowermost ice mass after some years. In sub-region (3) several small but comparably long glaciers are surging and some collide with a larger main glacier (e.g. Skamri or Sarpo Laggo) becoming a tributary. A wide range of terminus advance rates is also apparent. The latter is in particular evident in sub-region 4 (cf. Fig. 5) showing some very slowly advancing glaciers and others that advance rapidly. In this latter case the advancing North Crown Glacier has re-activated the ice remnants from a previous surge of a similar-sized neighbouring glacier into its own surge, resulting in a strong advance over a short period of time.

3.2 Identifying surge-type glaciers

It seems that neither advance rates nor flow velocities enable a clear identification of surge-type glaciers as the wide range of possible values (observed for surging glaciers) overlap with those observed at non-surge-type glaciers. Moreover, surge-type glaciers can have nearly any size and characteristic, from very small ($< 1 \text{ km}^2$) and steep, to large ($> 10 \text{ km}^2$) and flat. Another typical characteristic of most surge-type glaciers (e.g. those not flowing into a larger main glacier from the beginning) is their elongated tongue of uniform width after a surge (compared to their original geometry) and the way this extended tongue is separated from the main glacier by thinning a few years after the surge stopped. In general, the separation occurs at about $1/4$ to $1/3$ of the surge length when measured from the terminus, pointing to thicker ice at the surge front compared to the rest of the tongue (as ablation should be higher at lower elevations). In the animation, the post-surge separation of the ice mass in the ablation region looks like droplets that slowly separate from a dripping water tap, though for a liquid with a much higher viscosity than water.

The duration of the two surge phases (active and quiescent) varies considerably across the region. For example, in sub-region (2) from a one to two year advance period (in 2006/7) and a 30 year quiescent phase for Drenmang Glacier (see also Hewitt, 2007) to a now > 15 years advance period (starting around 1999) and a stagnant

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phase of only a few years for 1st Feriole Glacier. A long surge duration was also observed for a small valley glacier in Greenland (Jiskoot and Juhlin, 2009), but in general the surge characteristics of the glaciers in this region are different from those in Alaska or Svalbard described by Murray et al. (2003). It might thus be appropriate to introduce a new “Karakoram surge type”, having a long duration of the surge phase with slow to medium advance rates of the terminus and typical surge distances of a few km. However, several exceptions to this description exist even in the small region investigated here, especially for tributary glaciers that contribute to the flow of a larger main glacier anyway (e.g. Drenmang, Moni, South Skamri).

3.3 Surface elevation changes

On closer examination, surface elevation changes can also be followed along the lateral moraines. In sub-region 2 (Fig. 3), no elevation changes are visible for Choktoi Glacier over the 15 year-period, but surface lowering can be seen for the lower part of NS (despite the three glaciers that surged into it), Sarpo Laggo and Skamri glaciers (both in sub-region 3), and an increase is visible in the upper part of NS (above the Drenmang tributary), maybe as a result of the massive 2006 surge, blocking the ice flux at this location. Surface increase and later lowering is well visible for the upper part of the Drenmang Glacier in sub-region (2) and the North-Crown Glacier in sub-region (4), more or less revealing how the surge front is moving down glacier. These regions of thickening and lowering are also visible in Fig. 9 of the study by Gardelle et al. (2013), who determined elevation changes over the 2000–2008 period from DEM differencing.

3.4 Lakes and debris cover

Another form of variability can be seen for the numerous (hundreds) supra-glacial lakes and ponds covering the lower parts of Baltoro Glacier (in sub-region 1), NS (in sub-region 2) and several other glaciers. These lakes seem to be rather short lived (about 2–3 years) which restricts their use for determining flow velocities with feature tracking

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to a one-year period. Most of the lakes have about the same size but change their shape rather strongly within a year. For Baltoro Glacier it is apparent that supra-glacial lakes often form in zones of compressive flow (where larger tributaries join), indicating that surface meltwater is not efficiently drained. More stationary lakes can be seen outside of lateral moraines, but also their size changes over time. One glacier (Mundu) in sub-region (1) has regular and similar-sized patches of debris on its surface indicating periodic rock fall activity.

3.5 Accumulation region

Flow dynamics in the accumulation region are more difficult to follow due to lack of traceable features and the high variability of snow extent. However, some dynamic features are visible, especially in sub-region (1) below the image centre. These features include deep crevasses and high flow velocities in the steepest parts of glacier headwalls. The flow speed here is so high that the 2–3 year time step between images fails to provide the impression of continuous flow.

3.6 Shaking terrain

Finally, sub-region (2) is showing locally shaking terrain, mostly along mountain peaks and ridges. This is the result of artifacts in the DEM used for orthorectification of the satellite images and that different DEMs have been used. As this shaking is concentrated on regions outside of glaciers (i.e. “stable” terrain), an algorithm calculating flow velocity would obtain a considerable surface displacement in these regions, which need to be removed manually before accuracy assessment over stable terrain can be performed. The animated images clearly reveal such regions, thus helping in determining the quality of the orthorectification and the post-processing of velocity data (e.g. Kääh, 2005).

4 Discussion

4.1 Identifying surge-type glaciers

The Karakoram region is well known for its many surging glaciers, but counting them is challenging as the frequently used criteria for their identification only partly apply. The criteria can be divided into morphological and dynamic categories (e.g. Jiskoot, 2011). The former include: looped or distorted medial moraines, a glacier tongue that is covered by seracs during a surge, a post-surge disconnection of the tongue well behind the terminus, and rapid down-wasting after the surge with the formation of potholes and remaining stranded ice bergs (e.g. Yde and Knudsen, 2005). Dynamic criteria include (among others): the terminus advance rate, the total advance over a given period, the duration of the advance and retreat (or quiescent) phase, the relative advance compared to the pre-advance glacier length, absolute values of surface velocity, significant velocity changes in specific regions of a glacier, surge periodicity, and rapid thickness changes in the ablation and accumulation regions. For these dynamic criteria, the values for surging glaciers can be one to three orders of magnitude higher than for non-surge-type glaciers (e.g. Jiskoot, 2011). However, they can also be in a similar range thus limiting the possibilities for a clear separation.

Glaciers that have been classified as being of surge type according to the above criteria (typically only the morphologic approaches are used) or that have been observed to surge in the past, have also been analysed in regard to their topographic characteristics (e.g. area, perimeter, length, slope, median elevation) by Clarke et al. (1986) for glaciers in the Yukon Territory and Berrand and Murray (2006) or Rankl et al. (2014) for the Karakoram. The latter two studies revealed a tendency for surge-type glaciers to be longer, less steep, and more fully debris covered than non-surge-type glaciers of similar size.

When analysing glacier dynamics in sub-regions (2), (3) and (4) and focusing on glaciers with rapid advances and/or a long advance distance (km scale), it seems that many of the actively surging or surge-type glaciers in the Karakoram do not display

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most of the above criteria. They are often small (2–10 km² range) and debris free (apart from medial moraines), they have slopes ranging from flat (region 2) to steep (region 3), advance rates from slow to fast (e.g. 1st Feriole vs. Drenmang), variable morphological evidence of past surge activity (in particular the small and steep ones have none), “surge” durations from 1–2 to > 15 years, and sometimes partly very short stationary phases, i.e. some of them seem pulsating between two stages (e.g. Kotlyakov et al., 2008 and references therein). These differences from surging glaciers in other regions of the world might require adding a Karakoram surge-type category, and a discussion of how slow and prolonged the advance can be for it to be considered the outcome of a surge. How the behaviour of this type can be explained in terms of ice dynamics might be a subject for future research.

Regarding the characteristics of the surge-type glaciers described here (small, steep, debris free) compared to those found in other studies, it seems that this is related to a yet missing but required separation of the surging glaciers from the much larger main glaciers receiving the surges (see Fig. 3 in Rankl et al., 2014). In nearly all cases, the tributaries surge into a larger main glacier (e.g. Skamri, Sarpo Laggo, NS) creating the distorted and/or looped moraines on the surface. Interestingly, these larger glaciers show nearly stagnant terminus positions combined with down-wasting in the ablation region, implying that the mass contributed by the surges is not sufficient to have any effects down-glacier.

4.2 Climatic influences

Interpreting glacier changes in this region in climatic terms is challenging and not just because of the lack of climate data from high-elevation stations. It seems evident that nearly all glaciers (also small ones) are healthy as expressed by their either stable or advancing termini (Bhrambhatt et al., 2015; Rankl et al., 2014). This implies that past mass budgets have generally been close to zero or even positive (Janes and Bush, 2012). While this provides a link between the observed changes and climatic condi-

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tions, these glaciers might not show elevation changes that can be measured reliably using satellite data or repeat DEMs as they are too small. On the other hand, trend analysis of ICESat data (Gardner et al., 2013; Kääh et al., 2012) and volume changes derived from DEM differencing (Gardelle et al., 2013) reveal substantial thickening in the ablation area for most of the larger actively surging glaciers, consistent with the here reported changes. As the measured mass gain of these glaciers (the mass loss in the accumulation region is more difficult to quantify) is over a longer term in fact a mass loss, it would be more safe to exclude these glaciers from climate change impact studies if these are related to time scales shorter than a full surge cycle.

4.3 Repeat surges

Many of the glaciers in the study region have reportedly surged during the past century (cf. Copland et al., 2011) and historic satellite imagery (e.g. the MSS scene from 1977) reveals different extents of the surge-type glaciers analysed here. For example, 1st Feriole Glacier was in contact to Panmah Glacier back in 1977 and the high-resolution satellite image from 6. June 2014 available in Google Earth (Fig. 6) reveals that the glacier is still in full surge mode and might again re-establish contact with Panmah Glacier in two or three years, resulting in a ca. 40 year surge cycle. A tributary of Sarpo Laggo Glacier in sub-region 3 (Nr. 45 in Copland et al., 2011; Nr. 16 in Rankl et al., 2014) had been in contact with the main glacier back in 1977, 1991 and again in 2007, resulting in a ca. 15-year cycle. In Fig. 7 an image of its surge front from July 2006 is shown, about 1.5 years before the glacier came in contact with Sarpo Laggo Glacier. It would be interesting to analyse if surges occur regularly also for other glaciers in the region.

4.4 Special image conditions

Finally, it has to be noted that animations like the ones presented here over a period of 15 years are not possible everywhere. The animation includes ETM+ scenes from

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2004, 2006, and 2009 (see Table 1), all normally suffering from severe striping due to the malfunction of the ETM+ scan line corrector since 2003. Luckily, this striping has been reduced to a large extent (some artefacts are still visible) by USGS for these scenes, likely by replacing the missing information from other scenes. Surprisingly, this had no noticeable effect on the boundaries or surface features of the quickly changing glaciers, e.g. due to clouds or different snow conditions. It implies that great care has been taken to correct the striping in these three scenes (e.g. two of the ETM+ scenes are also in the Global Land Survey dataset of 2005 and 2010 and have been processed in this way) and/or that the replacement scenes were acquired close to the date of the corrected scenes, for example by Landsat TM.

Another important issue is the high-quality and consistent orthorectification of all satellite scenes by USGS. Although in sub-region (2) some mountains shake due to differences in the DEMs used for the correction, such effects are not noticeable in the other sub-regions, i.e. they stay within one pixel. Without this consistency it would not be possible to reveal glacier flow dynamics with such clarity.

4.5 Educational use of the animations

There is certainly some potential for using the animations also for educational purposes, for example regarding the displayed dynamic changes (glaciers, snow line, lakes, rivers). This requires knowledge about the number of scenes used and the time period covered (see Table 1). Remote sensing related questions might focus on the spectral properties of ice and snow and the false colour composites used (resulting in well-visible glaciers), spatial resolution and visibility of details, or the value of long-term time series and free data availability. The latter might be further explored in summer schools (e.g. Manakos et al., 2007) or classroom experiments (e.g. creating animations for other regions or with a different speed), as all image quick-looks that have been used here can be downloaded freely and individually (e.g. from earthexplorer.usgs.gov) and the required GIS and animation software is freely available as well.

5 Conclusions

This study discussed and presented (in the Supplement) animated satellite image sequences from four regions in the Karakoram mountain range. The high-repetition rate of 1/10s per frame gives the impression of a continuous flow and reveals the high variability in flow dynamics among the different glaciers with a clarity that is not possible from static images (side-by-side comparison) or colour coded glacier outlines from different points in time. Though changes are not determined in a quantitative way, the animations are likely of particular interest for educational purposes as the time-lapse mode reveals changes that are otherwise difficult to observe. Such animations might also be created for other regions in the world to reveal glaciers dynamics and interactions.

Whereas the largest and often debris-covered glaciers in the region (e.g. Baltoro, Biafo, Choktoi, Sarpo Laggo) show normal (laminar) flow characteristics, their tributaries and several small to medium-sized (and often debris free) glaciers show unstable flow with surge-like dynamics. The latter glaciers exhibit a continuum of terminus advance rates, surge and quiescent phase durations as well as mean surface slopes that differ from descriptions of surge-type glaciers in regions such as Alaska or Svalbard. In particular, the smaller surge-type glaciers often show no morphological evidence of surging such as looped or distorted medial moraines and their surges can only be recognized through time-series image analysis. Several of the larger glaciers with often completely debris-covered tongues (e.g. Nobande Sobonde, Sarpo Laggo, Skamri, K2 Glacier) have stationary fronts and show considerable surface lowering, despite the mass contributions from the surging tributaries. The study revealed that these large main glaciers are not surging themselves but get distorted in their flow by their surging tributaries.

Surges are generally out of phase and some glaciers seem to surge periodically with a repeat cycle of only a few decades. It thus seems advisable to remove surge-type glaciers from the sample when climate change impacts are investigated on a shorter

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time scale (e.g. elevation changes from DEM differencing). Several further geomorphologic changes are visible (e.g. short-lived supra-glacial lakes, variability of river beds, thickening and thinning of glaciers, regions of fast and slow flow, contribution of tributaries) that might be of interest for a more detailed analysis. The time series will certainly become more valuable in the future with further satellite scenes being added.

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Table 1. Overview of the Landsat scenes used to create the animations (Nr. 2–14) for the four sub-regions shown in Figs. 2 to 5. The MSS scene is added for completeness. Abbreviations: Sensor column: MSS: MultiSpectral Scanner, TM: Thematic Mapper, ETM+: Enhanced Thematic Mapper +, OLI: Operational Land Imager, dd.mm: day.month, Day: day number within a year, region codes in columns 7–10 denote 1: Baltoro, 2: Panmah, 3: Skamri, 4: Shaksgam, GLS: Global Land Survey.

Nr.	Sensor	dd.mm	Year	Day	Path-Row	1	2	3	4	Remarks
1	MSS	02.08.	1977	214	160-035	–	–	–	–	from GLS1975
2	TM	02.07.	1991	183	148-035	X	–	–	–	
3	TM	07.09.	1998	250	148-035	X	X	X	X	
4	ETM+	04.09.	2000	248	148-035	X	–	–	–	
5	ETM+	21.07.	2001	202	148-035	–	X	X	X	
6	ETM+	09.08.	2002	221	148-035	X	X	–	–	
7	ETM+	14.08.	2004	227	148-035	X	X	X	X	GLS2005, striping removed
8	ETM+	26.07.	2006	207	149-035	–	X	–	–	striping removed
9	ETM+	12.08.	2009	224	148-035	X	X	X	X	GLS2010, striping removed
10	TM	23.08.	2010	235	148-035	–	X	–	X	
11	TM	10.08.	2011	222	148-035	X	–	X	X	
12	OLI	14.07.	2013	195	148-035	X	X	X	X	

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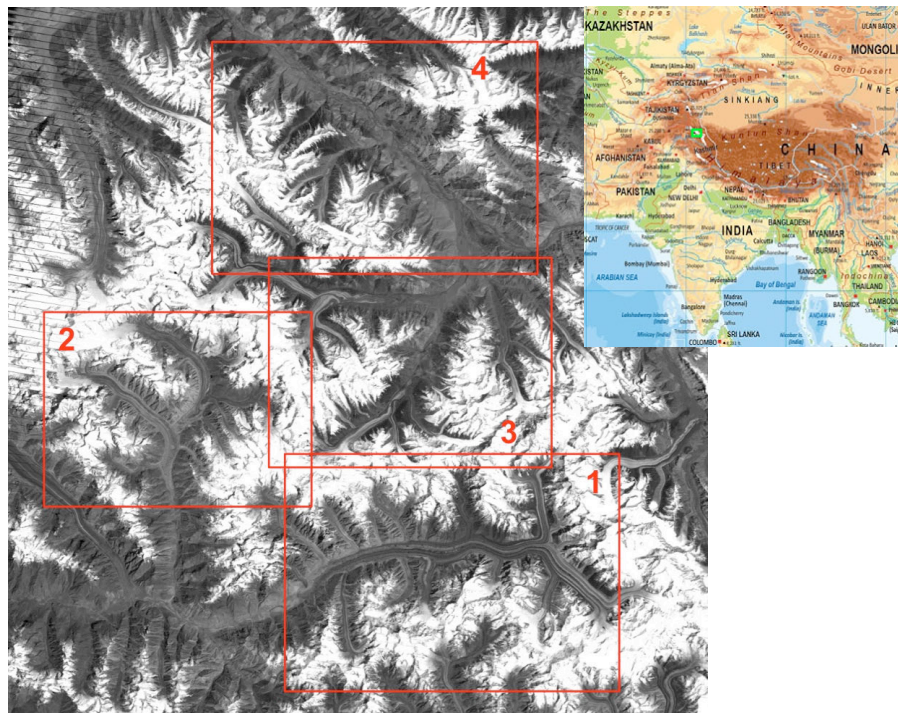


Figure 1. Landsat scene (pan-band) of the study region showing footprints of the four sub-regions depicted in Figs. 2 to 5. The green square in the inset shows the approximate location of the study region (map taken from www.worldmapsonline.com). Image centre is at 36° N, and 76.3° E.

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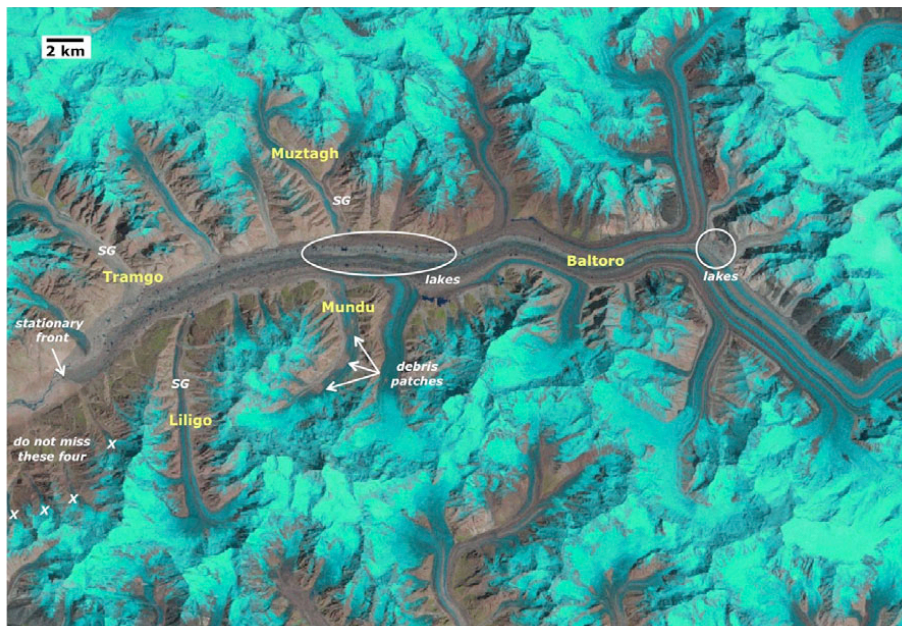


Figure 2. Sub-region 1 (Baltoro) shows the tongue of Baltoro Glacier and its surrounding tributaries. SG (orange): actively surging glacier, SG (white): surge-type glacier, A: advancing glacier. The Landsat scene 148-035 is from 14 August 2004.

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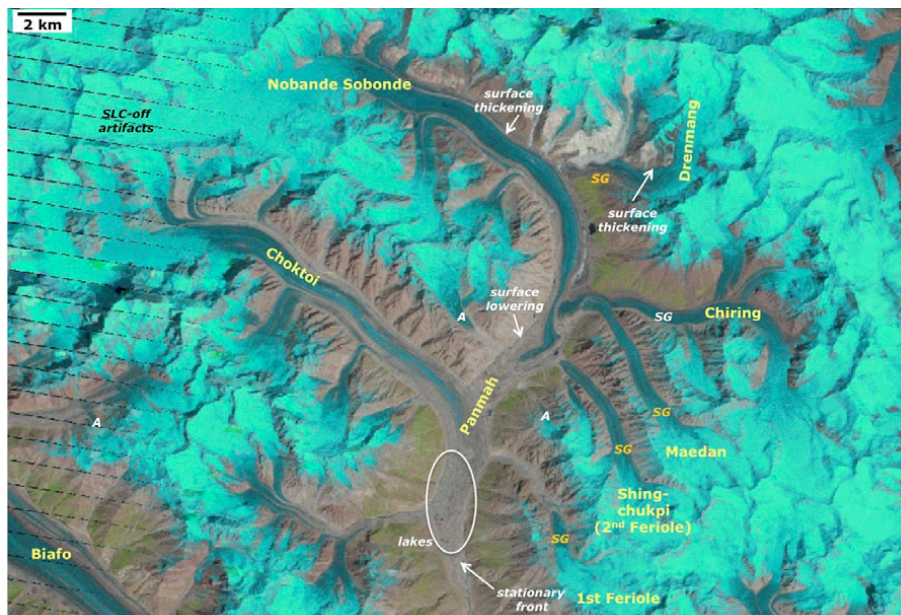


Figure 3. Sub-region 2 (Panmah) shows the region around Panmah and Choktoi glacier with surrounding tributaries; annotations and Landsat scene as in Fig. 2.

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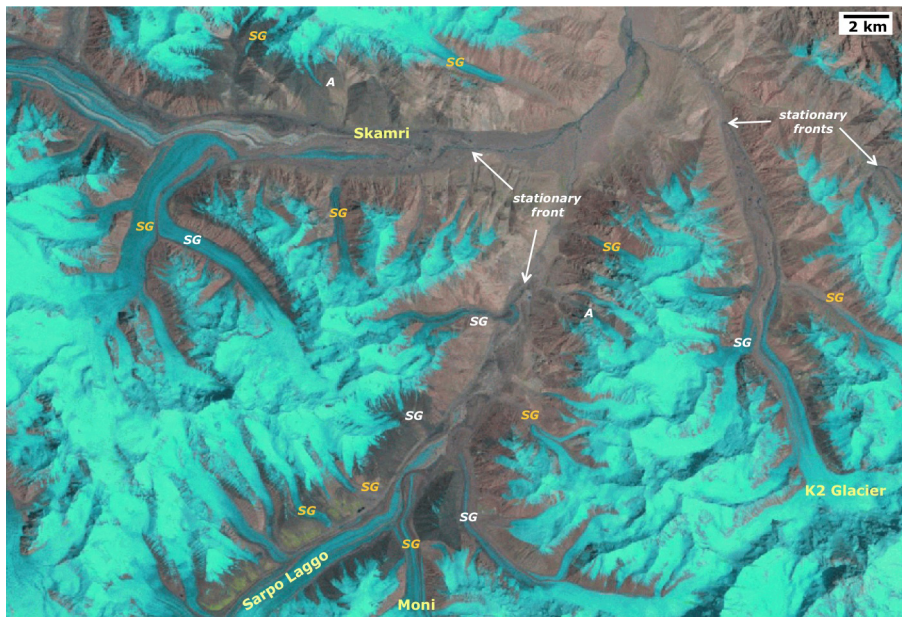


Figure 4. Sub-region 3 (Skamri) shows the region between Skamri and Sarpo Laggo glacier; annotations and Landsat scene as in Fig. 2.

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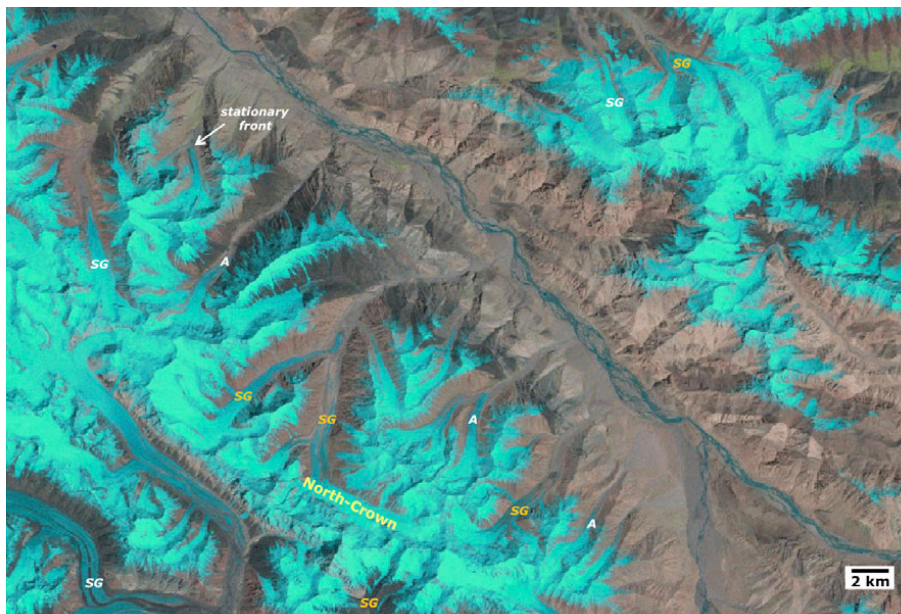
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Figure 5. Sub-region 4 (Shaksgam) shows the region to the north of Skamri Glacier to both sides of the Shaksgam valley; annotations and Landsat scene as in Fig. 2.



Figure 6. The still advancing (surging) tongue of 1st Feriole Glacier in the Panmah sub-region. The image is a screenshot from Google Maps acquired on 6 June 2014.

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Figure 7. An unnamed surging glacier in sub-region 3 (to the right of the centre) as seen from Moni Glacier, a surging tributary of Sarpo Lago Glacier (see Sect. 5.3 for details). To the left of the image is another unnamed surging glacier visible. The photo was taken in 2006 by Michael Beck (www.himalaya-info.org).

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