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 help demonstrating glacier flow dynamics for educational purposes. The animations reveal highly complex patterns of glacier flow and surge dynamics over a 22-year time period (1991-2013). In contrast to other regions, surging glaciers in the Karakoram are often small (around 10 km^2), steep, debris free, and advance for several years to decades 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

1.1 Visualizing glacier dynamics

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; Bhambri 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 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), 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; Quincey et al., 2015).

Although these representations of changing glaciers are scientifically sound and exact, they have some limitations in demonstrating dynamic aspects. 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 it is 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 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 two images taken a few years apart) for demonstrating glacier changes is common practice 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; Paul et al., 2015). 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 landscape changes in a time-lapse mode (e.g. world.time.com/timelapse2) including glacier flow and dynamic changes over large regions. This provides new insights and a more intuitive access to phenomena such as the mutual interaction of different glaciers, fast and slow flow of different glacier segments, advance and retreat patterns, down-wasting (i.e. surface lowering without retreat), and the dynamics of supra and pro-glacial lakes and river streams. Depending on the time step between the original images and the flow velocity of the glaciers, the impression of more or less continuous flow can be obtained by animating the individual images at high speed.

In this study animated sequences of orthorectified satellite images covering a 22-year time period (1991-2013) are used to demonstrate glacier dynamics and other landscape changes in four regions of the central Karakoram. 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 provide additional insight into glacier behaviour. There is also potential for using such animations for educational purposes by visualizing how glaciers flow and change 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 it is the only format that allows a looping of high-frequency animations with screen-size images. The format has recently become increasingly popular on the Internet (e.g. giphy.com) and in mobile communication (Isaac, 2015) for short repetitive animations due to its easy use (no special software required) and relatively small file size.

1.2 Surge-type glaciers

The Karakoram mountain range has been selected due to its many surging glaciers that display a very distinct dynamic behaviour (e.g. Copland et al. 2011; Gardelle et al., 2013; Hewitt, 2007; Rankl et al., 2014). According to Jiskoot (2011), a surge-type glacier oscillates between a period of slow or normal flow (for tens to hundreds of years) named the quiescent phase 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). During a surge a large amount of ice is transported from a reservoir area to a receiving area where it melts after a surge predominantly by down-wasting. All three components (time periods for both phases, velocities, terminus advance) reportedly vary over a wide range (e.g. Sharp, 1988), resulting in an unclear separation from non-surge-type glaciers (cf. Table 5 in Sevestre and Benn, 2015) that might, for example, just advance over an extended period of time (Meier and Post, 1969). A surge-type glacier in its quiescent phase can often also be identified from distortions of the normally parallel-aligned medial and/or lateral moraines (e.g. Grant et al., 2009; Kotlaykov et al., 2008). 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 (e.g. Hewitt, 2007). In the latter case it might be possible that the main glacier is - despite the surge-marks on its surface - not of surge-type.

The Karakoram region is well known for it's many surge-type glaciers (e.g. Copland et al., 2011; Hewitt, 2014), but counting them is challenging as the frequently used criteria for their identification only partly apply. Many studies have thus introduced a 'surge-index' to indicate the certainty that a specific glacier is of surge-type (cf. Sevestre and Benn, 2015). The evidence can be divided into geomorphological and dynamic categories (e.g. Jiskoot, 2011). The former include: looped or distorted medial moraines, a glacier tongue that is largely covered by crevasses and 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 inverse thickness changes in the ablation (mass gain) and accumulation (mass loss) 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. For this study a glacier is called 'surging' based on its well-identifiable strong and partly rapid advance. All of these glaciers have been identified as of surge-type or actively surging in previous studies (Copland et al., 2011; Gardelle et al. 2013; Rankl et al., 2014).

2. Study Region, Data Sets and Methods

The study region is located in the central Karakoram mountain range (Fig. 1) to the north of – and including – the large and well-studied Baltoro Glacier (Quincey et al., 2009 and references therein). Four regions are selected for the animations: (1) Baltoro, (2) Panmah, (3) Skamri / Sarpo Laggo, and (4) Shaksgam. All regions are well known for their many surge-type glaciers (cf. Copland et al. 2011 and 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). 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 behaviour might be attributable to an increase in precipitation (e.g. Janes and Bush, 2012), but the large number of actively surging glaciers in the region might also have non-climatic reasons (e.g. Hewitt, 2005; Jiskoot, 2011). A recent study by Sevestre and Benn (2015) has identified that glaciers in this region are located in the climatically 'correct' zone for surge-type glaciers. Further details about the topo-climatic characteristics of the region can be found in Hewitt (2014).

The study region is completely covered by Landsat scene 148-35 (path-row) and partly by scene 149-35 (Fig. 1). Useful Landsat scenes (sensors TM, ETM+ and OLI) acquired near the end of the ablation period (summer) are available for 13 individual years since 1991 and four further scenes for selected regions (see Table 1). For the animations provided in the supplemental material only a selection of scenes has been used to limit file size. The animations using the full set of scenes are provided on a separate webpage (http://xxx) along with the individual scenes. 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. 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, vegetation in green and bare terrain in pink to purple. All scenes are processed in a standardized processing line at USGS (with colours balanced) and are provided with extra files that include projection information and geolocation for easy import into GIS software.

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 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 seconds 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 scene from 2004). In general, the temporal difference between two images in the animation is one or two years, but two times it is three and once (from 2004 to 2008) four years (see Table 1).

3. Results

3.1 Observable 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 steady flow. Despite the well recognizable high velocity of the main glacier, its terminus remains in about the same position and supraglacial lakes on the surface appear and disappear. There are two surge-type glaciers (with instable flow) in the north and one in the south (Liligo) that has been studied in detail before (e.g. Belo et al., 2008). However, they are both too small to affect the main glacier in terms of deformed moraines. Four rather small glaciers in the south-west corner of the image (marked with an 'x') 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 the steady flowing versus surging glaciers. While the larger tongues of Biafo, Choktoi and Nobande Sobonde (NS) glaciers show the steady flow of non-surge-type glaciers, several (partly tributary) glaciers show unsteady fast flow with strong terminus advances (i.e. active surging), partly colliding with other glaciers and creating the well-known distorted and looped moraines (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. Well 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, 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 surging after the year 2000, others just finished their surge and showed the characteristic down-wasting of the quiescent phase with a separation of the lower-most part of the ice mass after some years. In sub-region (3) several small but comparably long glaciers are surging and some merge with a larger main glacier becoming a tributary for some time. A wide range of terminus advance rates is apparent as well. While one glacier (North Chongtar) in sub-region 3 (Fig. 4) advances very slowly (and might not be identified as surge-type from its advance rate), one glacier (North Crown) in sub-region 4 (Fig. 5) advances very rapidly and is clearly surging. In this latter case, ice remnants from a previous surge of a similar-sized neighbouring glacier was incorporated into its surge, resulting in a strong advance over a short period of time (cf. Quincey et al., 2015).

3.2 Identification of surging glaciers

The animations reveal that many glaciers have either stable termini or slightly advance while others show very rapid and/or strong advances that can be named an active surge. But a closer inspection shows that there is actually a continuum of advance rates with no clear separation between surging and just advancing glaciers. The same is true for advance durations that vary from short pulses (1-2 years) of rapid advance (Drenmang) to slow advances taking more than 10 or even 20 years (First Feriole, North Chongtar). In particular the latter also occurs for non-surge-type glaciers. Moreover, glaciers of nearly any size seem to surge, from small (<1 km^2) and steep, to large (>10 km^2) and flat. Geomorphological evidence such as distorted or looped moraines can also only be found for a few glaciers. Hence not all of the advancing glaciers in the animations must be surging glaciers. A maybe better possibility for separating surging from just advancing / retreating glaciers is their post-surge behaviour (i.e. the quiescent phase).

As the animations reveal (for glaciers that do not flow into another glacier from the beginning), the way the extended tongue is down-wasting and disintegrating after a surge is rather specific. It seems (e.g. for Liligo in Fig. 2 or Shingchukpi in Fig. 3) that the entire surged ice mass is transformed into dead ice after a surge and rapidly down-wasting, similar to the ice resulting from a calving event. After some years, this down-wasting is separating the lower part of the surged ice mass from an upper part at about ¼ to 1/3 of its length (when measured from the terminus). This is pointing to thicker ice near the terminus compared to the rest of the tongue, as ablation should be even higher at the lower elevations of the terminus (assuming clean ice). This specific pattern of dead-ice down-wasting after a surge is rather unique for surge-type glaciers and allows distinguishing them from other glaciers. In the case tributaries join flow with another glacier from the beginning (Drenmang in Fig. 3, Moni and South Skamri in Fig. 4), marks of surges are well traceable as looped moraines. Based on the above evidence, surge-type glaciers are marked in Figs. 2 to 5 with ‘SG’ (in orange for an active surge) and only advancing glaciers with an ‘A’. Application of other criteria might come to a different assignment.

3.3 Surface elevation changes

On closer examination, surface elevation changes can also be recognized along the lateral moraines. In sub-region 2 (Fig. 3), no elevation changes are visible for Choktoi glacier over the 22 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 (sub-region 3), and a slight 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 Drenmang in sub-region (2) and North-Crown in sub-region (4), both revealing how a surge front is moving down glacier. These regions of thickening and lowering are also well 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) supraglacial lakes and ponds covering the lower parts of Baltoro Glacier (sub-region 1), NS (sub-region 2) and some other glaciers. These lakes seem to be rather short lived (about 2-3 years) limiting their use for determining flow velocities from feature tracking to a one-year period. Most of the lakes have about the same size but their shape varies rather strongly from scene to scene. For Baltoro Glacier it is apparent that supraglacial lakes often form in zones of compressive flow (where larger tributaries join), indicating that surface meltwater is not efficiently drained. Stationary lakes outside of lateral moraines show 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. They are related to crevasses in the often very steep parts of glacier headwalls and reveal very high flow velocities. The flow speed here is high enough that the 1 to 3 year time step between images fails to provide the impression of continuous flow.

3.6 Movement of stable terrain

Finally, sub-region (2) is locally showing movement of terrain that should be stable, mostly along mountain peaks and ridges. This is likely the result of different DEMs that have been used for orthorectification of the satellite images. As the movement 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 for an entire time series and the post-processing of velocity data (e.g. Kääb, 2005).

4. Discussion

4.1 Surge-type glaciers

In agreement with the study by Sevestre and Benn (2015) and several previous investigations (e.g. Copland et al., 2011; Hewitt, 2007; Quincey et al., 2011; Rankl. et al, 2014), the central Karakoram has a high abundance of surge-type glaciers of which many have been actively surging in the past 20 years. As 'normal' glacier advances are basically a consequence of changed climatic conditions while surges largely result from internal mechanisms (e.g. Jiskoot, 2011; Meier and Post, 1969; Raymond, 1987; Sharp, 1988), it is important to distinguish both glacier types. However, the animations reveal a large heterogeneity of the surging glaciers and their surges in terms of size, advance rates, surge durations, hypsometry, exposition, etc. that clearly overlap with the characteristics of advances from non-surge-type glaciers. This difficulty in distinguishing both glacier types will result in different views on the reasons for the advance, independent of the still limited understanding of surge mechanisms. At least for some of the glaciers the specific post-surge dead-ice down-wasting pattern might be a reliable indicator for identification.

The assignment of a glacier as surge-type (white 'SG' in Figs. 2 to 5), surging (orange 'SG') or just advancing ('A') in this study, is based on the inventory by Copland et al. (2011), the studies by Rankl et al. (2014) and Quincey et al. (2014), geomorphological evidence (e.g. distorted moraines or the post-surge down-wasting pattern) and historic satellite images (e.g. the MSS scene from 1977). However, glacier 14 in Fig. 6 of the study by Rankl et al. (2014) is in this study only marked as advancing rather than surging and this certainly subjective. On the other hand, glacier 15 in their study (North Chongtar) is listed there as surge-type but is actually slowly advancing since the 1970s, i.e. for more than 40 years. This gives rise to the question how slow and prolonged an advance can be for it to be considered the outcome of a surge?

Previous studies that have characterized surge-type glaciers according to their topographic characteristics (e.g. area, length, slope, debris cover) have found a tendency for surge-type glaciers to be longer, less steep, with more branches and being more fully debris covered than non-surge-type glaciers of similar size (e.g. Clarke et al., 1986; Barrand and Murray, 2006; Rankl et al., 2014; Sevestre and Benn, 2015). In contrast, many of the surge-type or surging glaciers in the study region are comparably small (2-20 km^2 range) and steep, debris free (apart from medial moraines), and have single or dual-basin accumulation regions. It is assumed that this difference is also a result of a missing separation between the surging tributaries and the not-surging main glaciers in previous studies. Such a separation would also be required for a precise topographic characterization of the surging tributaries.

An interesting consequence of the separation issue would be that large glaciers that are not of surge type (e.g. NS or Sarpo Laggo) carry all the surge marks (e.g. looped or deformed moraines), while those glaciers that really surge have none of the marks and can only be identified when observed during a surge. Furthermore, all of the large and debris-covered glaciers (NS, Sarpo Laggo and Skamri) show nearly stagnant terminus positions combined with well visible down-wasting in their ablation region. This implies that the mass contributed by the surging tributaries is not sufficient to have any effects down-glacier.

Excluding some exceptions and generalizing the wide range of surge characteristics to some extent, the surges in this part of the Karakoram can be characterized as having a long duration of the active phase (several years to decades) with slow to medium advance rates of the terminus and typical surge distances of a few km. In this regard they differ from the surge types described previously by Murray et al. (2003) for Alaska and Svalbard and might thus also have different reasons (Quincey et al., 2015).

4.2 Climatic influences

Interpreting glacier changes in this region in climatic terms is challenging not just because of the lack of climate data from high elevation stations. It seems evident that nearly all glaciers (including the 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 conditions, 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; Kääb 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 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 seems appropriate to exclude surging glaciers from climate change impact studies that 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 latest 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 in subregion 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

The animations like the ones presented here over a period of 22 years are not possible everywhere. The time series includes ETM+ scenes from 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. This striping has been reduced to a large extent (some artefacts are still visible) by USGS for these scenes (see Fig. 3), 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 and/or that the replacement scenes were acquired close to the date of the corrected scenes.

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

4.5 Educational use of the animations

There is certainly some potential for using the animations 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 supplementary material) animated satellite image sequences from four regions in the Karakoram mountain range. The high-repetition rate of 1/10 second 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 time-lapse mode of the animations reveals changes that are otherwise difficult to observe. Such animations might also be used for educational purposes and 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, Choktoi, Sarpo Laggo) show normal (steady) 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 durations and topographic characteristics that overlap with non-surge-type glaciers, thus making their identification difficult. 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. On the other hand, some of the larger glaciers with debris-covered tongues (e.g. Nobande Sobonde, Sarpo Laggo, Skamri), have stationary fronts and show considerable surface lowering, despite the mass contributions from the surging tributaries. The study revealed that some of these large glaciers are not surging themselves but get their moraines distorted from surging tributaries.

Surges are generally out of phase with one another and some glaciers seem to surge periodically with repeat cycles of a few decades. It thus seems advisable to exclude surge-type glaciers from the sample when climate change impacts are investigated on a shorter time scale (e.g. elevation changes from DEM differencing). Several further geomorphologic changes are visible (e.g. short-lived supraglacial lakes, variability of river beds, thickening and thinning, regions of fast and slow flow) that might be of interest for a more detailed analysis. The time series will likely become more valuable in the future with further satellite scenes being added.

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Tables

Table 1: Overview of the Landsat scenes used to create the animations (Nr. 3 and 8 to 13 without 9) for the supplementary material for the four sub-regions shown in Figs. 2 to 5. Scenes Nr. 2, 4 to 7 and 9 are available as individual images from http://www.xxx. The MSS scene is only added for completeness. Abbreviations: Sensor column: MSS: Multi-Spectral 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	07.08.	1990	219	149-035	-	X	-	-	path 149
3	TM	19.08.	1991	231	148-035	X	X	X	X	used for the animation
4	TM	07.07.	1993	188	148-035	X	X	X	X	
5	TM	17.07.	1994	198	149-035	-	X	-	-	path 149
6	TM	01.09.	1996	245	148-035	X	X	X	X	fresh snow
7	TM	18.07.	1997	199	148-035	X	X	X	X	
8	TM	07.09.	1998	250	148-035	X	X	X	X	
9	ETM+	04.09.	2000	248	148-035	X	-	-	-	
10	ETM+	21.07.	2001	202	148-035	-	X	X	X	
11	ETM+	09.08.	2002	221	148-035	X	X	-	-	
12	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, path 149
9	TM	04.10.	2008	278	148-035	X	X	X	X	not used for the animation
10	ETM+	12.08.	2009	224	148-035	X	X	X	X	GLS2010, striping removed
11	TM	23.08.	2010	235	148-035	-	X	X	X	
12	TM	10.08.	2011	222	148-035	X	-	X	X	
13	OLI	14.07.	2013	195	148-035	X	X	X	X	

This table and the caption will change if supplementary material with a larger file size (>50 MB) can be uploaded.

Figure captions

Fig. 1
Landsat scene of the study region from 2004 showing footprints of the four sub-regions depicted in Figs. 2 to 5. The black square in the inset shows the location of the study region in the Karakoram mountain range (map taken from Google Earth). The image centre is at 36 N, and 76.3 E.

Fig. 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 Aug. 2004.

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

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

Fig. 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.

Fig. 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.

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

Figures

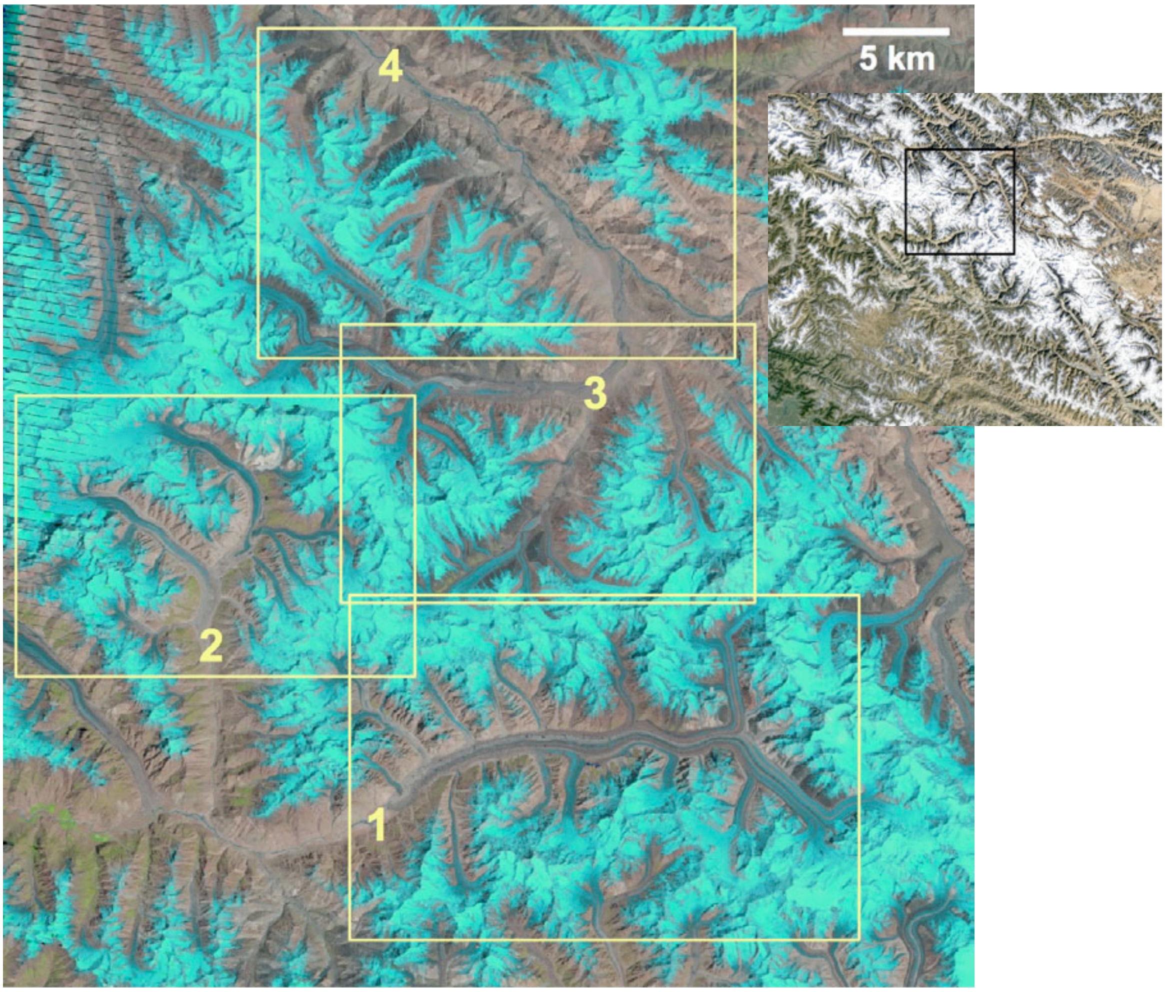

Fig. 1

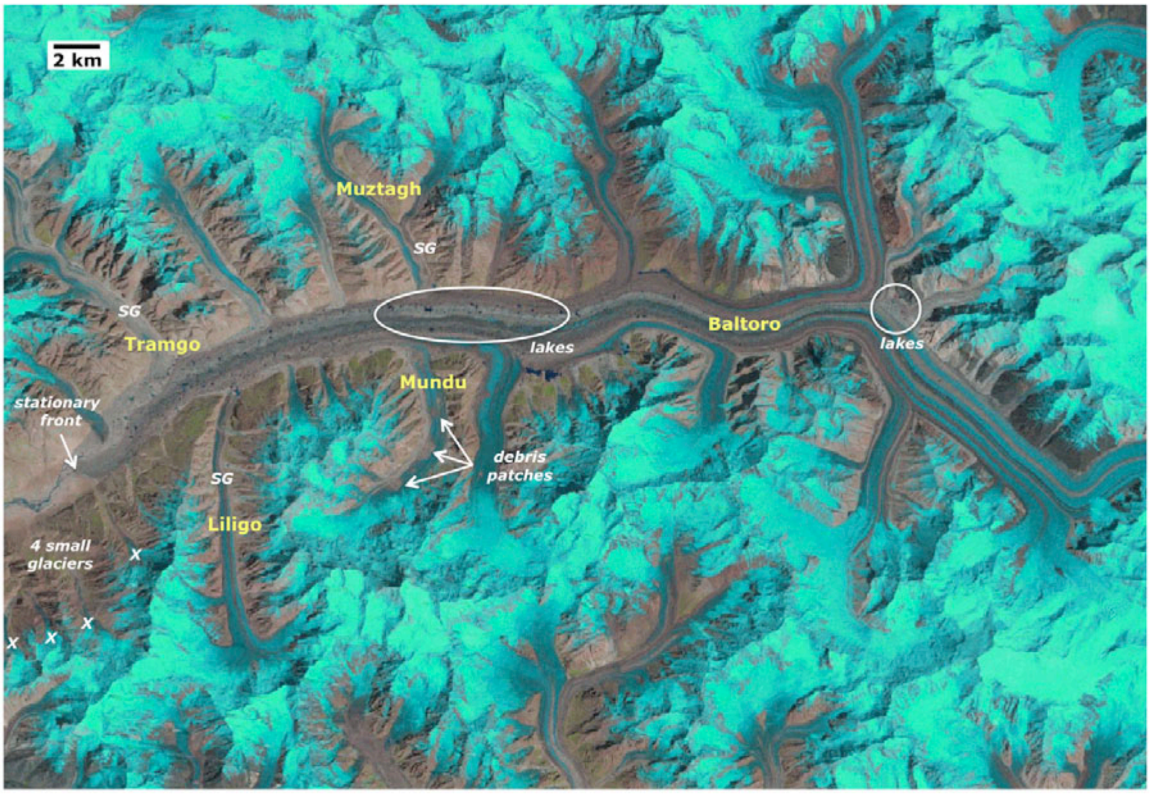
2 km
Muztagh
SG
SG
Tramgo
lakes
Baltoro
lakes
Mundu
stationary front
debris patches
SG
Liligo
4 small glaciers
X
X
X
X

Fig. 2

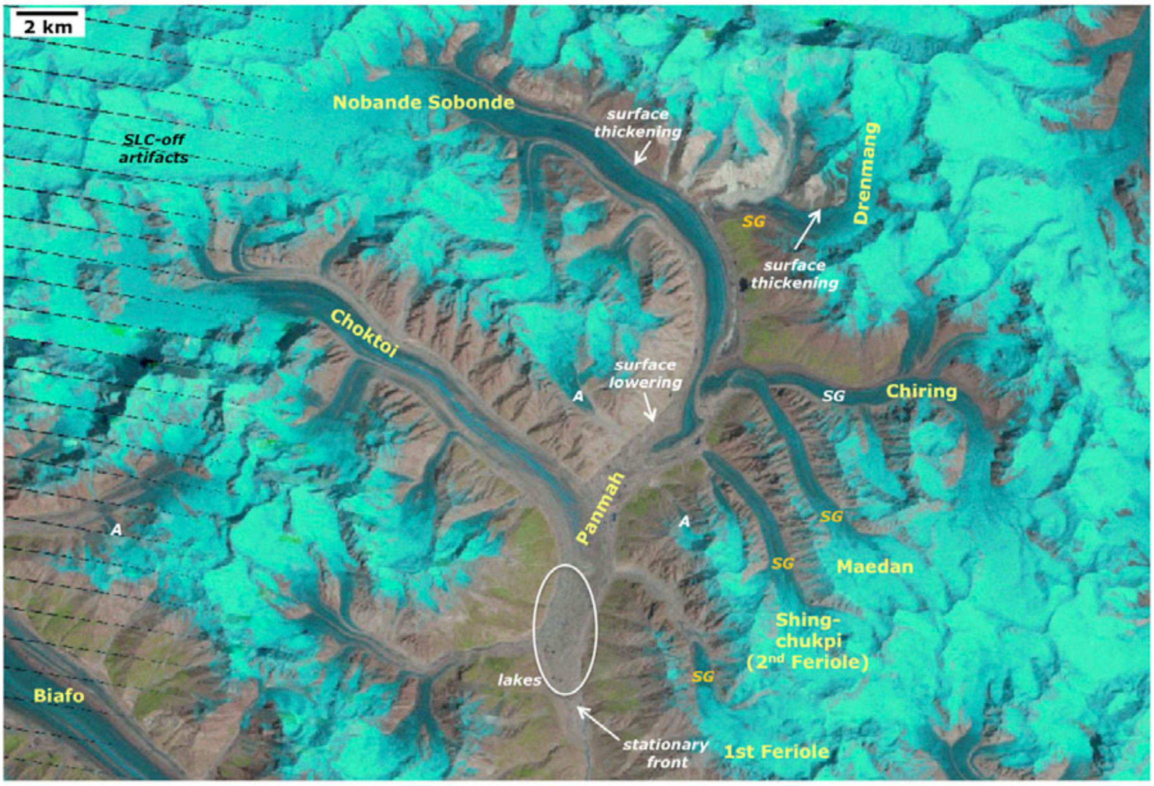
2 km
Nobande Sobonde
surface thickening
SLC-off artifacts
Drenmang
SG
surface thickening
Choktoi
surface lowering
A
SG
Chiring
Panmah
A
A
SG
SG
Maedan
Shing-chukpi (2nd Feriole)
lakes
SG
stationary front
1st Feriole
Biafo

Fig. 3

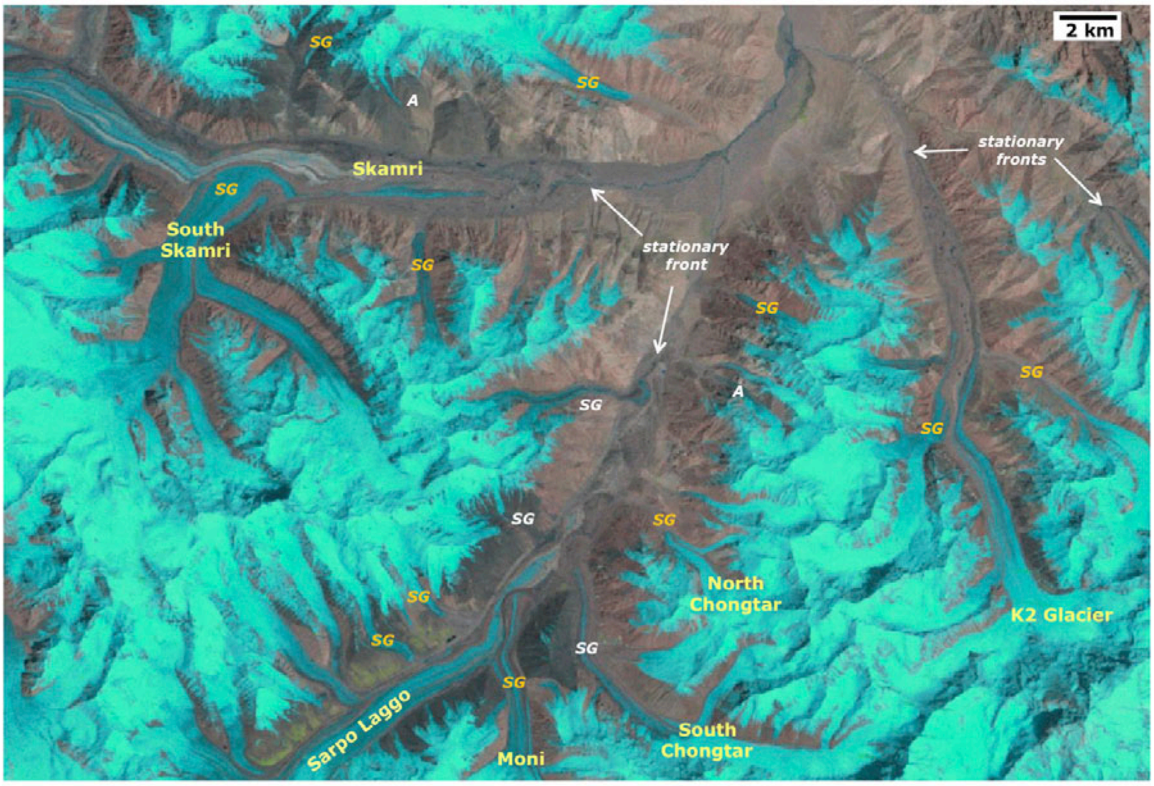
2 km
SG
SG
A
Skamri
SG
South Skamri
stationary fronts
stationary front
SG
SG
SG
A
SG
SG
SG
SG
North Chongtar
K2 Glacier
SG
SG
SG
SG
Sarpo Laggo
Moni
South Chongtar

Fig. 4

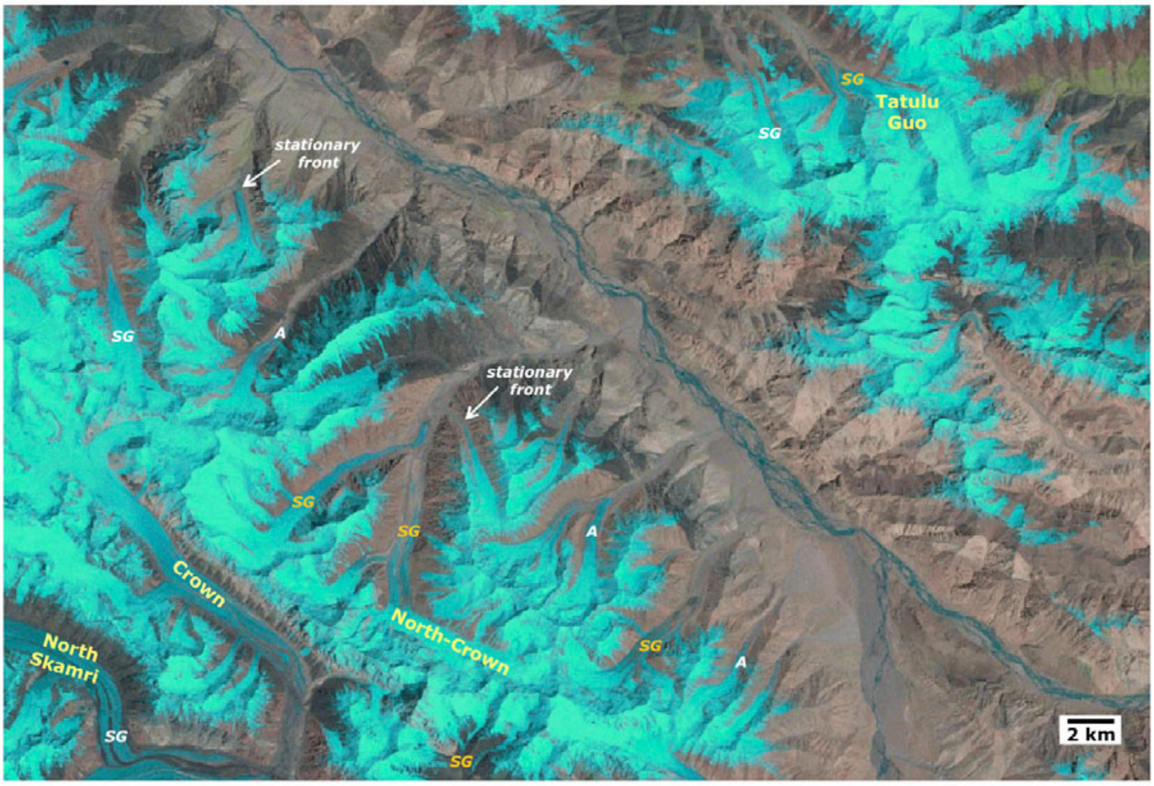
SG
Tatulu Guo
SG
stationary front
SG
A
stationary front
SG
SG
A
Crown
North-Crown
SG
A
North Skamri
SG
SG
2 km

Fig. 5

Fig. 6

Fig. 7