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

Frank Paul

Department of Geography, University of Zurich, Zurich, Switzerland

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).

fp 21 8 15 11:14 AM **Deleted:** might

fp 21 8 15 11:14 AM **Deleted:** to demonstrate

fp 21 8 15 11:14 AM **Deleted:** revealed

fp 21 8 15 11:14 AM **Deleted:** 15

fp 21 8 15 11:14 AM **Deleted:** 1998

fp 21 8 15 11:14 AM **Deleted:** ... [1]

fp 21 8 15 11:14 AM **Deleted:** or a surge is resulting in looped moraines

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 oscil-

fp 21 8 15 11:14 AM **Deleted:** what is going on.

fp 21 8 15 11:14 AM **Deleted:** also

fp 21 8 15 11:14 AM **Deleted:** at least

fp 21 8 15 11:14 AM **Deleted:** these days

fp 21 8 15 11:14 AM **Deleted:**).

fp 21 8 15 11:14 AM **Deleted:** into such

fp 21 8 15 11:14 AM **Deleted:** surge characteristics,

fp 21 8 15 11:14 AM **Deleted:** ,

fp 21 8 15 11:14 AM **Deleted:** .

fp 21 8 15 11:14 AM **Moved (insertion) [1]**

fp 21 8 15 11:14 AM **Deleted:** One of

fp 21 8 15 11:14 AM **Deleted:** most fascinating regions

fp 21 8 15 11:14 AM **Deleted:** such an application is the

fp 21 8 15 11:14 AM **Deleted:** with

fp 21 8 15 11:14 AM **Deleted:** (e.g.

fp 21 8 15 11:14 AM **Deleted:** surging lates 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; Kotlyakov 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 in-

fp 21 8 15 11:14 AM
Deleted: ,

fp 21 8 15 11:14 AM
Deleted: Their

fp 21 8 15 11:14 AM
Deleted: behaviour

fp 21 8 15 11:14 AM
Deleted: becomes evident

fp 21 8 15 11:14 AM
Deleted: alignment of

fp 21 8 15 11:14 AM
Deleted: .

fp 21 8 15 11:14 AM
Moved (insertion) [2]

fp 21 8 15 11:14 AM
Moved (insertion) [3]

fp 21 8 15 11:14 AM
Deleted: 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 animations for educational purposes, basically for everybody interested in seeing how glaciers flow and how glaciers are changing through time.

fp 21 8 15 11:14 AM
Moved up [1]: 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.

fp 21 8 15 11:14 AM
Deleted: 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. ... [2]

fp 21 8 15 11:14 AM
Deleted: Fig. 1

fp 21 8 15 11:14 AM
Deleted: surging

fp 21 8 15 11:14 AM
Deleted: for an overview see

fp 21 8 15 11:14 AM
Deleted: or

fp 21 8 15 11:14 AM
Deleted: Several valley glaciers in this region exhibit extended periods (>10 years) of strong advance and/or fast flow (Rankl et al., 2014).

crease 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

fp 21 8 15 11:14 AM
Deleted: a
fp 21 8 15 11:14 AM
Deleted: explanation
fp 21 8 15 11:14 AM
Deleted: also
fp 21 8 15 11:14 AM
Deleted: ten individual years since 1998 and one scene from 1991 (see Table 1).
fp 21 8 15 11:14 AM
Deleted: The scene from 1991 was only used for the Baltoro sub-region.
fp 21 8 15 11:14 AM
Deleted: way
fp 21 8 15 11:14 AM
Deleted: several
fp 21 8 15 11:14 AM
Deleted: listing
fp 21 8 15 11:14 AM
Deleted: . Most images have too much snow cover to allow creation of glacier outlines for an inventory
fp 21 8 15 11:14 AM
Deleted: 2004
fp 21 8 15 11:14 AM
Deleted: sometimes (depending on cloud conditions)
fp 21 8 15 11:14 AM
Deleted: or even more. The respectiv ... [3]
fp 21 8 15 11:14 AM
Deleted: for each of the four regions ... [4]
fp 21 8 15 11:14 AM
Deleted: **Terminus**
fp 21 8 15 11:14 AM
Deleted: laminar
fp 21 8 15 11:14 AM
Deleted: supra-glacial
fp 21 8 15 11:14 AM
Deleted: come
fp 21 8 15 11:14 AM
Deleted: go
fp 21 8 15 11:14 AM
Deleted:), but
fp 21 8 15 11:14 AM
Deleted: leave an impact on
fp 21 8 15 11:14 AM
Deleted: south of the Baltoro terminus
fp 21 8 15 11:14 AM
Deleted: normal versus fast-
fp 21 8 15 11:14 AM
Deleted: (or
fp 21 8 15 11:14 AM
Deleted:)
fp 21 8 15 11:14 AM
Deleted: laminar

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.

fp 21 8 15 11:14 AM
Deleted: see also …ewitt, 2007). The ... [5]

fp 21 8 15 11:14 AM
Deleted: lowermost…ower-most part ... [6]

fp 21 8 15 11:14 AM
Deleted: Identifying surge-type

fp 21 8 15 11:14 AM
Deleted: It seems …he animations re ... [7]

fp 21 8 15 11:14 AM
Deleted: a larger main…nother glaci ... [8]

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).

fp 21 8 15 11:14 AM
Deleted: ... [9]

fp 21 8 15 11:14 AM
Deleted: followed…ecognized along ... [10]

fp 21 8 15 11:14 AM
Deleted: supra-glacial…upraglacial ... [11]

fp 21 8 15 11:14 AM
Deleted: These features include dee ... [12]

fp 21 8 15 11:14 AM
Deleted: **Shaking**

fp 21 8 15 11:14 AM
Deleted: locally shaking …ovement ... [13]

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

fp 21 8 15 11:14 AM
Deleted: Identifying

fp 21 8 15 11:14 AM
Moved up [3]: 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.

fp 21 8 15 11:14 AM
Deleted: 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

fp 21 8 15 11:14 AM
Moved up [2]: 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 p ... [14]

fp 21 8 15 11:14 AM
Deleted: rapid thickness changes in ... [15]

fp 21 8 15 11:14 AM
Deleted: ... [16]

fp 21 8 15 11:14 AM
Deleted: being of surge type

fp 21 8 15 11:14 AM
Deleted: the above criteria (typically ... [17]

fp 21 8 15 11:14 AM
Deleted: perimeter,

fp 21 8 15 11:14 AM
Deleted: median elevation) by Clark ... [18]

fp 21 8 15 11:14 AM
Deleted: and

fp 21 8 15 11:14 AM
Deleted: .

fp 21 8 15 11:14 AM
Deleted: When analysing glacier dy ... [19]

fp 21 8 15 11:14 AM
Deleted: actively surging or surge-ty ... [20]

fp 21 8 15 11:14 AM
Deleted: of the surging glaciers fron ... [21]

fp 21 8 15 11:14 AM
Deleted: , NS) creating

fp 21 8 15 11:14 AM
Deleted: distorted and/or

fp 21 8 15 11:14 AM
Deleted: moraines on the surface. In ... [22]

fp 21 8 15 11:14 AM
Deleted: the

fp 21 8 15 11:14 AM
Deleted: , implying

fp 21 8 15 11:14 AM
Deleted: surges

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 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

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.

- fp 21 8 15 11:14 AM **Deleted:** and
- fp 21 8 15 11:14 AM **Deleted:** also
- fp 21 8 15 11:14 AM **Deleted:** larger
- fp 21 8 15 11:14 AM **Deleted:** would be more safe
- fp 21 8 15 11:14 AM **Deleted:** these
- fp 21 8 15 11:14 AM **Deleted:** one or
- fp 21 8 15 11:14 AM **Deleted:** Glacier
- fp 21 8 15 11:14 AM **Deleted:** Finally, it has to be noted that
- fp 21 8 15 11:14 AM **Deleted:** 15
- fp 21 8 15 11:14 AM **Deleted:** animation
- fp 21 8 15 11:14 AM **Deleted:** Luckily, this
- fp 21 8 15 11:14 AM **Deleted:** ,
- fp 21 8 15 11:14 AM **Deleted:** in these three scenes (e.g. two of the ETM+ scenes are also in the Global Land Survey dataset of 2005
- fp 21 8 15 11:14 AM **Deleted:** 2010 and have been processed in this way) and /
- fp 21 8 15 11:14 AM **Deleted:** , for example by Landsat TM.
- fp 21 8 15 11:14 AM **Deleted:** shake
- fp 21 8 15 11:14 AM **Deleted:** they stay

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.

fp 21 8 15 11:14 AM
Deleted: also

fp 21 8 15 11:14 AM
Deleted: animations are likely of particular interest for educational purposes as the

fp 21 8 15 11:14 AM
Deleted: Biafo,

fp 21 8 15 11:14 AM
Deleted: laminar

fp 21 8 15 11:14 AM
Deleted: and quiescent phase

fp 21 8 15 11:14 AM
Deleted: as well as mean surface slopes

fp 21 8 15 11:14 AM
Deleted: differ from descriptions of

fp 21 8 15 11:14 AM
Deleted: in regions such as Alaska or Svalbard

fp 21 8 15 11:14 AM
Deleted: Several

fp 21 8 15 11:14 AM
Deleted: often completely

fp 21 8 15 11:14 AM
Deleted: , K2 Glacier)

fp 21 8 15 11:14 AM
Deleted: main

fp 21 8 15 11:14 AM
Deleted: in their flow by their

fp 21 8 15 11:14 AM
Deleted: a

fp 21 8 15 11:14 AM
Deleted: cycle

fp 21 8 15 11:14 AM
Deleted: only

fp 21 8 15 11:14 AM
Deleted: remove

fp 21 8 15 11:14 AM
Deleted: supra-glacial

fp 21 8 15 11:14 AM
Deleted: of glaciers

fp 21 8 15 11:14 AM
Deleted: , contribution of tributaries

fp 21 8 15 11:14 AM
Deleted: certainly

Acknowledgements

This study has been performed in the framework of the ESA project Glaciers_cci (4000109873/14/I-NB). All Landsat data were obtained from USGS. S. Allen, P. Rastner and the scientific editor M. Sharp provided helpful comments to improve the manuscript. I would also like to thank B. Marzeion, D. Quincey and one anonymous referee for their constructive reviews.

References

Barrand, N.E., and Murray, T.: Multivariate controls on the incidence of glacier surging in the Karakoram Himalaya, Arct., Antarct., Alp. Res., 38, 489-498, 2006.

Baumann, S., Winkler, S., and Andreassen, L.M.: Mapping glaciers in Jotunheimen, South-Norway, during the 'Little Ice Age' maximum, Cryosphere, 3, 231-243, 2009.

Belò, M., Mayer, C., Smiraglia, C., and Tamburini, A.: The recent evolution of Liligo glacier, Karakoram, Pakistan, and its present quiescent phase, Ann. Glaciol., 48, 171-176, 2008.

Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D.P., Srivastava, D., and Pratap, B.: Heterogeneity in glacier response in the Shyok valley, northeast, Cryosphere, 7, 1384-1398, 2013.

R. M. Brahmbhatt, I. M. Bahuguna, B. P. Rathore, S. K. Singh, A. S. Rajawat, R. D. Shah, and J. S. Kargel: Satellite monitoring of glaciers in the Karakoram from 1977 to 2013: an overall almost stable population of dynamic glaciers, Cryosphere Discuss., 9, 1555-1592, 2015.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., and Scheel, M.: The State and Fate of Himalayan Glaciers, Science, 336, 310-314, 2012.

Clarke, G.K.C., Schmok, J.P., Ommanney, C.S.L., and Collins, S.G.: Characteristics of surge-type glaciers, J. Geophys. Res., 91 (B7), 7165-7180, 1986.

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(4), 503-516, 2011.

Diolaiuti, G., Pecci, M., and Smiraglia, C.: Liligo Glacier, Karakoram, Pakistan: a reconstruction of the recent history of a surge-type glacier, Ann. Glaciol., 36, 168-172, 2003.

Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain of Karakoram glaciers in the early twenty-first century, Nat. Geosci., 5, 322-325, 2012.

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

Gardner, A.S., Moholdt, G., Cogley, J.G., Wouters, B., Arendt, A.A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W.T., Kaser, G., Ligtenberg, S.R.M., Bolch, T., Sharp, M.J., Hagen, J.O., van den Broecke, M.R., and Paul, F.: A consensus estimate of glacier contributions to sea level rise: 2003 to 2009, Science, 340 (6134), 852-857, 2013.

Grant, K.L., Stokes, C.R. and Evans, I.S.: Identification and characteristics of surge-type glaciers on Novaya Zemlya, Russian Arctic. J. Glaciol., 55(194), 960-972, 2009.

Hewitt, K.: Glaciers receive a surge of attention in the Karakoram Himalaya, EOS Transactions, American Geophysical Union, 79(8), 104-105, 1998.

Hewitt, K.: The Karakoram Anomaly? Glacier Expansion and the 'Elevation Effect,' Karakoram Himalaya, Mt. Res. Dev., 25, 332-340, 2005.

Hewitt, K.: Tributary glacier surges: an exceptional concentration at Panmah Glacier, Karakoram Himalaya, J. Glaciol., 53, 181-188, 2007.

Hewitt, K.: Glaciers of the Karakoram Himalaya. Glacial Environments, Processes, Hazards and Resources, Springer, Dordrecht, 2014.

Isaac, M.: GIFs go beyond emoji to express thoughts without words. The New York Times, Technology, 3. Aug. 2015 (http://nyti.ms/1HlXkOZ), 2015.

Iturrizaga, L.: Trends in 20th century and recent glacier fluctuations in the Karakoram Mountains, Z. Geomorph., 55, Suppl. 3, 205-231, 2011.

Janes, T.J. and Bush, A.B.G.: The role of atmospheric dynamics and climate change on the possible fate of glaciers in the Karakoram, J. Climate, 25, 8308-8327, 2012.

Jiskoot, H.: Glacier Surging. In: Singh, V.P., Singh, P., and Haritashya, U.K. (Eds.): Encyclopedia of Snow, Ice and Glaciers. Springer, Heidelberg, 415-428, 2011.

Jiskoot, H., and Juhlin, D.T.: Surge of a small East Greenland glacier, 2001-2007, suggests Svalbard-type surge mechanism, J. Glaciol., 55 (191), 567-570, 2009.

Jiskoot, H., Murray, T., and Boyle, P. J.: Controls on the distribution of surge-type glaciers in Svalbard, J. Glaciology, 46, 412-422, 2000.

Kääb, A. (2005): Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya, Remote Sens. Environm., 94 (4), 463-474, 2005.

Kääb, A. and Vollmer, M.: Surface geometry, thickness changes and flow fields on creeping mountain permafrost: automatic extraction by digital image analysis, Permafrost Periglac., 11, 315-326, 2000.

Kääb, A., Isakowski, Y, Paul, F, Neumann, A., and Winter, R.: Glaziale und periglaziale Prozesse: Von der statischen zur dynamischen Visualisierung, Kartographische Nachrichten, 53 (5), 206-212, 2003.

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, 2012.

Kotlyakov, V.M., Osipova, G.B., and Tsvetkov, D.G.: Monitoring surging glaciers of the Pamirs, central Asia, from space, Ann. Glaciol., 48, 125-134, 2008.

MacGillivray, C.: How Psychophysical perception of motion and image relates to animation practice. IEEE Proceedings of the International Conference on Computer Graphics, Imaging and Visualisation (CGIV 2007), 81-88, 2007.

McNabb, R. and Hock, R.: Alaska tidewater glacier terminus positions, 1948-2012, J. of Geophys. Res., F119, 153-167, 2014.

Meier, M.F. and Post, A.: What are glacier surges? Can. J. Earth Sci., 6 (4), 807-817, 1969.

Mukhopadhyay, B. and Khan, A.: Rising river flows and glacial mass balance in central Karakoram, J. Hydrol., 513, 192-203, 2014.

Murray, T., Strozzi, T., Luckman, A., Jiskoot, H., and Christakos, P.: Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions, J. Geophys. Res., 108 (B5), 2237, doi:10.1029/2002JB001906, 2003.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T.W. and Haeberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31, L21402, doi:10.1029/2004GL020816, 2004.

Paul, F. and 24 others (2015): The Glaciers Climate Change Initiative: Algorithms for creating glacier area, elevation change and velocity products. Remote Sens. Environm., 162, 408-426.

Quincey, D.J., Copland, L., Mayer, C., Bishop, M., Luckman, A., and Belo, M.: Ice velocity and climate variations for Baltoro Glacier, Pakistan. J. Glaciol., 55, 1061-1071, 2009.

Quincey, D.J., Braun, M., Glasser, N.F., Bishop, M.P., Hewitt, K., and Luckman, A.: Karakoram glacier surge dynamics, Geophys. Res. Lett., 38, L18504, doi:10.1029/2011GL049004, 2011.

Quincey, D.J., Glasser, N.F., Cook, S.J. and Luckman, A.: Heterogeneity in Karakoram glacier surges, DOI: 10.1002/2015JF003515, 2015.

Racoviteanu, A.E., Paul, F., Raup, B., Khalsa, S.J.S., and Armstrong, R.: Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA, Ann. Glaciol., 50, 53-69, 2010.

fp 21 8 15 11:14 AM
Deleted: in press

fp 21 8 15 11:14 AM
Deleted: .

Rankl, M., Kienholz, C., and Braun, M.: Glacier changes in the Karakoram region mapped by multimission satellite imagery, Cryosphere, 8, 977-989, 2014.

Raymond, C.F.: How do glaciers surge? A review, J. Geophys. Res., 92 (B9), 9121-9134, 1987.

Scambos, T.A., Dutkiewicz, M.J., Wilson, J.C. and Bindschadler, R.A.: Application of image cross-correlation to the measurement of glacier velocity using satellite image data, Remote Sens. Environm., 42, 177-186, 1992.

Sevestre, H. and Benn, D.I.: Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging. J. Glaciol, 61 (228), 646-662, 2015.

Sharp, M.: Surging glaciers: behaviour and mechanisms. Progr. Phys. Geogr., 12, 349-370, 1988.

Wulder, M. A., Masek, J. G., Cohen, W. B., Loveland, T. R., and Woodcock, C. E.: Opening the archive: How free data has enabled the science and monitoring promise of Landsat, Remote Sens. Environm., 122, 2-10, 2012.

Yde, J.C. and Knudsen, N.T.: Glaciological features in the initial quiescent phase of Kuannersuit Glacier, Greenland, Geogr. Ann., 87A (3), 473-485, 2005.

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.

fp 21 8 15 11:14 AM
Deleted: 2-14

fp 21 8 15 11:14 AM
Deleted: 2

fp 21 8 15 11:14 AM
Deleted: 02

fp 21 8 15 11:14 AM
Deleted: 1991

fp 21 8 15 11:14 AM
Deleted: 183

fp 21 8 15 11:14 AM
Deleted: -

fp 21 8 15 11:14 AM
Deleted: -

fp 21 8 15 11:14 AM
Deleted: -

fp 21 8 15 11:14 AM
Deleted: 3

fp 21 8 15 11:14 AM
Deleted: 4

fp 21 8 15 11:14 AM
Deleted: 5

fp 21 8 15 11:14 AM
Deleted: 6

fp 21 8 15 11:14 AM
Deleted: 7

fp 21 8 15 11:14 AM
Deleted: 9

fp 21 8 15 11:14 AM
Deleted: 10

fp 21 8 15 11:14 AM
Deleted: -

fp 21 8 15 11:14 AM
Deleted: 11

fp 21 8 15 11:14 AM
Deleted: 12

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).

fp 21 8 15 11:14 AM
Deleted: (pan-band)

fp 21 8 15 11:14 AM
Deleted: green

fp 21 8 15 11:14 AM
Deleted: approximate

fp 21 8 15 11:14 AM
Deleted: www.worldmapsonline.com). Image

Review by Ben Marzeion

The paper presented by Paul is somewhat unusual for TC, since it is more about communication within science, and to the public, than about new scientific findings. It is not so much that the image sequences presented in the paper add scientific insight per se; the (important) point is rather that the information – which quantitatively needs to be extracted using other methods – becomes a lot more accessible and intuitive. This point is also acknowledged by the author.

I am convinced that there needs to be room in a journal like TC for this kind of publication, but this should be an editorial decision. Given the format of TC, I also believe it is justified to be published as a research article; but should there be reservations, I can imagine that the author might be able to shorten the manuscript and to publish it as a brief communication.
I agree that it would be possible to convert the ms into a brief communication, but this would require rather substantial changes to the text and maybe a re-review. As the review by D. Quincey identified several points that might warrant a 'normal' publication in TC I would prefer to stay with the current format.

The manuscript is very well written, and I only have a few suggestions/questions that should be addressed before acceptance.

General comment:
• The greatest value of the submission probably is found in the animated images in the supplement. They are great – but I think there are two changes that might enhance their use: (i) add a progressing bar showing the time line (at least with start and end year), (ii) add a break (perhaps 2-3 frames) between end and beginning of the sequence. (I also find the sequences very quick, and slowing down the frame rate might be good – but this is probably a matter of taste, and hard to say without trying.)
Indeed, it is not only a matter of taste; different speeds also reveal different aspects of the flow dynamics. As also mentioned in the response to the review by D. Quincey, inserting empty frames at the end would introduce a stroboscope effect that is hard to watch. Any other markers of progressing time will be difficult to follow (and distracting from the flow dynamics), as the time period of the entire animation is too short (0.8 sec). Creating time-series with a different frame rate is possible but would exclude them from the supplementary material as the 50 MB space is already fully used.

As a compromise, I will provide the individual images (plus some new ones) on a separate server so that anybody can use its preferred animation speed and annotation. A further point was to show the results that can be obtained with a minimum amount of processing using freely available software. This should also facilitate the 'do it yourself' idea that is required for related teaching / classroom experiments.

I think particularly adding a bar is essential, as the uneven distribution of images in time (P2602, L23-25) implies a non-linear time line.
As mentioned above, there is no way to follow such a time bar, as the frame rate is too high. Moreover, for the visual perception it does not really matter if the temporal difference between the images is 1, 2 or 3 years and unevenly distributed, as the brain will average the differences out.

Specific comments:

• P2600 L4: I would say that the sequences do not necessarily provide new insights in these phenomena, but they make the insights more intuitive and accessible.

I fully agree with the latter point, but also think that seeing a glacier flow at about 800 million times its normal speed (25 years in 1 sec) IS a new insight in itself. Converting the 'normal' (quantitative) colour-coded maps of glacier flow or elevation changes to real surface flow, dynamic interactions of tributaries, frontal advance, mass transfer or down-wasting is in my opinion very difficult. So actually seeing how this takes place in a high-speed mode (with all the mutual interactions) is in my opinion providing several new insights.

To give one specific example, I was very surprised to see the very high flow velocities in steep accumulation regions of many glaciers (e.g. the southern tributaries of Baltoro). I think this has not been reported before (based on velocity maps) so I would argue this is a new insight.

• Fig. 1: The green square in the inset is very small; perhaps you can zoom a bit further into the map shown in the inset.

The inset and the main figure will be revised and improved.

• P2603 L4 (and elsewhere): The term laminar is a bit ambiguous, I think, because based on Reynolds number, I am relative sure also surging glaciers show laminar (as opposed to turbulent) flow. Admittedly, I don't have a better word...

I agree that laminar could be misleading in this regard and will think of a better word (maybe stable or steady flow?).

• P2603 L7: why mention the name of Liligo particularly, but not the two northern ones?

There was no specific reason for it apart from the availability of more detailed studies about this glacier and hence a chance that its name is known.

• P2604 L20-21: It could also be related to the debris distribution, which itself could be affected by the surge.

In principle yes, but for the examples discussed here debris cover is not present at the surface.

• Sect. 3.2 and 4.1 have the same heading, and Sect. 3.2 contains actually not much information on how to identify surge-type glaciers (instead, it is mostly discussed what would not work). The two sections are also of similar content to some degree, and I would suggest merging them.

I agree that there is some overlap between these two sections and will revise them. In the results section I will have a focus on the observations (new title: Surging glaciers), while I will describe the implications of the observations and the context to other studies in the discussion section.

Response to the review by Duncan Quincey

This is an unusual submission that contributes more to the literature than is necessarily apparent at first glance. First, it highlights that small and debris-free glaciers also surge - most recent studies on surging in the Karakoram focus on large and often debris-covered glaciers because they are easily identified in medium to coarse resolution satellite imagery. Second, it gives some useful information on surge return periods, which is generally lacking for this region (although historical reports and papers are relatively untapped I suspect). Third, it emphasises that surging glaciers are difficult to integrate into studies of climate-glacier coupling, and recommends they are excluded from such analyses. Therefore, despite this paper not conforming to a 'normal' research article, I would be pleased to see it published, and only have a handful of relatively minor comments that I hope will improve it.
Thank you for this positive evaluation.

P2598
Line 10: 'might help to demonstrate'... I think you can be more certain and remove the word 'might'.
Agreed.

P2599
Line 9: 'what is going on' is probably better phrased as 'morphological changes' or similar
Yes, agreed. Will be replaced with 'in demonstrating dynamic aspects.'

Line 26 delete 'these days'?
Yes, of course.

P2600
Line 6 (and elsewhere in this paper): probably 'surface lowering' is more technically correct than 'down-wasting'
Yes, surface lowering could also be used. But I think down-wasting is more than surface lowering, it also implies that the extent of the ice is more or less unchanged, i.e. surface lowering without retreat. This can actually be very clearly followed for the post-surge phase of several glaciers. The ice mass that is down-wasting is more or less decoupled dead ice showing otherwise a stable extent.

P2601
Line 1: remove the word 'basically' and replace with 'and'?
Agreed, good idea.

Line 4 (and elsewhere in this paper): if possible it would be better to remove references to yourself e.g. 'to my knowledge'
Yes, agreed and removed.

Lines 11-12: I think you can remove this last sentence. Why would you publish a discussion with only initial perspectives?
I think this has been written here because more detailed studies are required for a more substantial discussion. But I agree that the sentence could also be removed.

Lines 14-15: should 'and including' have commas before and after?
That might be well the case. I am happy to add them

P2603
Lines 9-11: can you label and refer to these four glaciers in the appropriate figure?
Yes, of course.

P2604
Lines 11-13: do surge velocities really overlap with those of non-surge glaciers? Not in my experience...
This will likely depend on the criteria used to identify a glacier as surge-type. Some of the glaciers in the region advance very slowly but over several decades (e.g. North Chongtar started its advance in 1970) while others advance rapidly (2-3 years) and have high surface flow velocities (e.g. South Chongtar, Chiring or Drenmang).

Lines 22-25: I'm not sure you need to include this analogy - suggest removal
Although I like the analogy as it might also include a physical explanation for this kind of surges, I will remove it as also the anonymous reviewer suggested to remove it.

Line 26 onward: I'm not sure I follow this sentence. Are you saying that one glacier has a 30 yr quiescence and 2 yr surge whereas another has a 15 yr surge and a few yrs quiescence? Perhaps you can word this better?
Yes, this was the point. I will rewrite it to get it clear.

On another matter, is the 15 yr advance really a surge? Or is it simply an advance? I'd suggest the latter given those timescales...
I would say yes, it is a surge, but as already mentioned above it depends to some extent on the criteria used to define a surge. The frontal advance rate or advance duration is certainly not good indicators. There is simply too much variability here. But when a heavily crevassed surface, distorted moraines, or an advance in the km range are used as a criterion, the assignment might be more evident. The study by Hewitt (2007) and the spatial pattern of mass changes revealed from DEM differencing by Gardelle et al. (2013) also clearly assign it to a surge-type glacier being in its active phase since 2000. Maybe also check the nice time series in Google Earth (one example is shown in Fig. 6).

P2605
Lines 1-9: Here you are touching on the fact that glacier surges cannot be neatly pigeonholed. I think you should state this, and leave it at that, rather than suggesting a new 'Karakoram surge type' - fundamentally, many surges in the region do not conform to your description (so the term would be misleading), but also there are more 'types' than we could ever find categories for.
I fully agree and will describe the different types of surging glaciers in another study.

P2606
Line 2:'supra-glacial' does not need hyphenating
Ok, thanks.

Section 3.6: I'm not sure this section adds anything and think it should be removed
I think this is actually a rather important observation for all kinds of calculations. For example, the accuracy assessment of velocity fields should give no flow on

stable terrain (i.e. off-glaciers). By using the here presented animations one can see both the consistency of the orthorectification for the entire time series and the regions that are not stable-terrain despite being off-glaciers.

P2608
Lines 2 and 12 and elsewhere: do you show us surface elevation data anywhere? I think you have to be careful assuming that because the glaciers are small, they are steep. Probably you are right, but your data do not show it.
Surface elevation data are indeed not shown here. Can I assume that everybody is familiar with checking topography in Google Earth? I will then add this as a source of information for the stated steepness.

P2609
Line 25: Why 'finally'? Is this a hangover from a previous draft?
No, the finally has no special meaning and will be removed.

Section 4.4: I'm also not sure this section is really required. It is background (methodological?) information
I agree that this section can be shortened somewhat and will do it. However, I would like to keep it, as I encourage application of this method in other regions and image availability, quality, and consistency of the orthorectification might be different elsewhere. In particular the good correction of the 3 ETM+ SLC-off scenes are worth mentioning, as they were essential for the animations.

P2611
Line 26: probably worth clarifying they are out of phase 'with one another'
Yes, agreed.

Figure 1: The regional map is poor - can you digitise something rather than use this map product? And zoom in more to focus on the HKH belt?
Yes, the in-set map will be exchanged and will get a close up.

The underlying image needs a scale-bar, and could be presented in colour?
Agreed, a scale bar will be added and a colour version provided.

Figure 6: needs a scale bar. And can you cross-reference this image to Figure 2?
It actually has one (in the lower left corner), but I agree it is rather small and I will increase it. The glacier will be marked in Figs. 1 and 3.

Also, why do you choose 2004 imagery for these figures?
There was no particular reason for it apart from being cloud-free and demonstrating the good correction (with some remaining artifacts) of the ETM+ SLC-off scenes that were essential for these animations (see also reply to the comment to Section 4.4.

Can you not use some of the (radiometrically improved) OLI imagery that has no striping?
Radiometrically the image quicklooks used in this study are all very similar and I think showing the striping is important as a guide to what is visible in the animations.

Supplementary

I strongly suggest you insert a time-gap at the end of every loop, as it takes a good few seconds or longer to work out where the first and last images are in each sequence. And perhaps slow them down? Or provide two speeds - one slower one for orientation (training of the eye) and the second at full speed? Given you put these forward for educational purposes, you need to make sure that the inexperienced viewer can follow what is happening for themselves.

The basic idea for providing only this high-speed version was that several aspects of glacier dynamics can only be seen here and that all images used are freely available at earthexplorer.usgs.gov. There is also a 50 MB limit of supplemental material and I have already used it. Inserting a time gap at the end (with empty frames) would result in a strobe effect causing eye-damage and a headache after a few seconds. There might be other possibilities (e.g. repeating the last image several times), but they would increase the file size. There is certainly the possibility to also use different (slower) animation speeds or frame rates, but this is also a matter of personal taste. As a compromise, I have decided to additionally provide the individual images on a separate server so that anybody being interested can compile its own animation time series from it.

A scale-bar wouldn't go amiss on the images either...

The disadvantage is that every annotation stands out like a 'flying above the scene' emblem and is thus distracting. It will also be difficult to follow the changes in a particular region and see the scale bar at the same time. For this reason all subsets are also shown in the paper with a scale bar. But I will try it and think about it.

Response to the review by the anonymous reviewer

The paper of F. Paul presents animated glacier flow time series for several Karakoram regions using imagery from the Landsat archive. The animations are great and useful on many levels, however, their presentation is not ideal. Currently, the main results are found in the supplementary materials, while much less important elements are found in the main paper. Some paragraphs contain details (how old is a certain image format, which button needs to be pressed in a certain program, etc.) that could go into an appendix or possibly into supplementary materials.
I agree that the paper is largely a description of what can be seen in the images, but I hope with the background given on visual perception and the wide range of surge-type glaciers described it also adds on the current knowledge for this region.

Other paragraphs have a review character, and the corresponding content could often be shortened or removed. Overall, I think, the topic would be better served if the paper were boiled down and published in a short communications format.

If the paper were published in the current format, it would be good to see additional quantitative aspects. For example, the discussion mentions characteristics of the surge-type glaciers identified (size, slope, etc). Having a more quantitative analysis of these parameters, similar to what has been done in previous work, would strengthen the paper. In any case, it would be great to see the fascinating movies hosted on a website.
I fully agree that a more detailed analysis of quantitative aspects would be worthwhile, but we intend to do this in another study presenting the new glacier inventory with topographic attributes for the entire Karakoram region. Just using the numbers from this yet unpublished study is maybe not a good idea. However, I have shortened and condensed some of the sections as also requested by the other reviewers.

P2598 L. 1: It seems that such movies (or at least "flicker" images) have been used regularly in presentations for visualization purposes, or just by the researcher themselves to get familiar with their study area. To my knowledge, however, there are no papers published that focus on this specific topic.
I fully agree with this statement. As I have also used animations regularly but found nothing on this specific topic in the literature, I decided to introduce it with this study.

L. 11: Revealed should be reveal
Done.

L. 20 & following lines: The introduction, especially its first part, seems lengthy. For example, I am not sure whether the human brain or the time lapse camera paragraphs are required at all. Also consider removing sentence parts that are not required, such as "basically for everybody interested in seeing. . .", "the very old (> 25 years)", "but to my knowledge", etc.
I will shorten the 'wordy' parts of the introduction. However, I would like to keep the sections on visual perception, the human brain and time-lapse photography, as these are important to introduce the animations and how they work.

P 2599:

L. 9: “in demonstrating what is going on” should be, for example, “in revealing the processes”
Done.

P 2600:
L. 25: Consider replacing the word “laminar” with “steady” or something similar. The term laminar is at least confusing. Note that even non surge-type glaciers can vary their speed over time, so “steady” is not ideal, either.
I will replace it with ‘steady’ (or stable?).

P 2601:
L. 6: “becoming” -> “become”
Done.

P 2602:
L. 4: “and partly also”. Remove the “also”. Throughout the manuscript, consider removing all the filler words as well as informal words that are not required (e.g., “luckily” later on).
Agreed and done.

P 2603:
L. 6: “come and go” -> disappear and reappear
L. 8: “Leave an impact” -> “affect”
Done.

P 2604:
L. 4: “collide with” -> “merge with”
Done.

L. 19-22: Needs to be read multiple times to be understood. Consider reformulating.
Agreed. It might get clearer when following the animations. I will maybe add a figure.

L. 22-24. Remove entirely.
Ok.

P 2605:
L. 5: “Karakoram surge type”: I would refrain from adding additional types. Don’t your movies rather suggest that the idealized “surge-type” and “non-surge type” glaciers mark the two end-members of a continuum, with a multitude of types in between?
Yes, I agree. I will remove it here and come back to it in another study.

L. 26: delete “which restricts their use. . .
Done.

P 2606:
L. 1: “but change their shape” -> “but their shape varies”
L. 13. “so high” -> “high enough” or “sufficiently high”
Done.

L. 15. Consider removing this section completely. If kept, replace “shaking” with a word that doesn’t automatically relate to earthquakes in this context. “wobbling” or simply “moving” could work.

P. 2609: L. 8: “more safe” -> “appropriate” or “advised”

Done.