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Worldwide widespread decadal-scale decrease of glacier speed revealed using repeat optical satellite images

T. Heid and A. Kääb

Department of Geosciences, University of Oslo, Box 1047 Blindern, 0316 Oslo, Norway

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Correspondence to: T. Heid (torborgh@geo.uio.no)

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Worldwide decadal-scale decrease of glacier speed

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Abstract

Matching of repeat optical satellite images to derive glacier velocities is an approach that is much used within glaciology. Lately, focus has been put into developing, improving, automating and comparing different image matching methods. This makes it now possible to investigate glacier dynamics within large regions of the world and also between regions to improve knowledge about glacier dynamics in space and time. In this study we investigate whether the negative glacier mass balance seen over large parts of the world has caused the glaciers to change their speeds. The studied regions are Pamir, Caucasus, Penny Ice Cap, Alaska Range and Patagonia. In addition we derive speed changes for Karakoram, a region assumed to have positive mass balance and that contains many surge-type glaciers. We find that the mapped glaciers in the five regions with negative mass balance have decreased their speeds over the last decades, Pamir by 43 % in average per decade, Caucasus by 8 % in average per decade, Penny Ice Cap by 25 % in average per decade, Alaska Range by 11 % in average per decade and Patagonia by 20 % in average per decade. Glaciers in Karakoram have generally increased their speeds, but surging glaciers and glaciers with flow instabilities are most prominent in this area.

1 Introduction

Deriving glacier surface velocities from optical satellite images using image matching is well established within glaciology. In the beginning manual methods were used (Lucchitta and Ferguson, 1986), but later automatic techniques took over. Bindschadler and Scambos (1991) and Scambos et al. (1992) were the first to use automatic image matching techniques to derive glacier velocities. They used normalized cross-correlation (NCC) based on the work of Bernstein (1983). Later, different image matching techniques have been applied for this purpose. Most studies have used the NCC technique (e.g. Scambos et al., 1992; Kääb, 2002; Copland et al., 2009; Skvarca et al., 2003; Berthier et al., 2005), some have used least square matching (Kaufmann and

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Ladstädter, 2003; Debella-Gilo and Kääb, 2011b), and lately frequency domain methods have become more common (Rolstad et al., 1997; Scherler et al., 2008; Haug et al., 2010; Herman et al., 2011; Quincey and Glasser, 2009) especially after the development of COSI-Corr (Leprince et al., 2007).

Most studies have focused on specific glaciers or smaller glacier regions, and only a few studies so far have focused on deriving glacier surface velocities for larger regions and comparing those (Kääb, 2005; Copland et al., 2009; Scherler et al., 2011b,a). However, since much focus is put into developing, improving and automating image matching techniques to make them well suited for image matching of glaciers (e.g. Leprince et al., 2007; Debella-Gilo and Kääb, 2011a,c; Haug et al., 2010; Heid and Kääb, 2011; Scherler et al., 2008) and also on comparing image matching techniques to find the methods that produce best results for glaciers (Heid and Kääb, 2011), it is now possible to focus on comparing glacier velocities within large regions and also between regions to improve our knowledge about glacier dynamics and its variation in space and time.

Using repeat optical satellite images to investigate annual glacier speed changes has one important advantage over using differential interferometric synthetic aperture radar (DInSAR), a technique that has immensely progressed our understanding of glacier flow (Rott, 2009). Because the coherence time is much longer for optical images than the phase coherence time is for SAR images, it is in most areas of the world possible to derive annual speeds using optical satellite images taken one year apart. DInSAR usually requires images days or at the maximum two months apart. Using optical satellite images it is thus less need to take seasonal speed variations into account when investigating whether annual glacier speeds are changing. Concerning coherence times, offset tracking based on repeat radar magnitude images lies in between optical matching and radar interferometry, but has else also a very large potential for global-scale mapping and monitoring of glacier flow (Quincey et al., 2009).

Glacier velocities are connected to mass balance because the mass flux through a cross section of a glacier equals the mass balance upstream of the cross section

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when a glacier is in balance (Paterson, 1994). In theory, negative mass balance therefore gives reduced ice flux under equilibrium conditions. Mass balance estimates have been strongly negative over large parts of the world for the last decades (e.g. Käser et al., 2006; Lemke et al., 2007; Bahr et al., 2009; WGMS, 2009), and we hypothesize that this negative mass balance has caused glaciers in many regions to slow down, at least on regional averages. To test this hypothesis, we select five glacier regions where the mass balance has been negative over the last decades. These regions are Pamir with a mass balance of Abramov glacier of $-0.53\,\mathrm{m\,w.e.\,a^{-1}}$ from 1980 to 1997 (WGMS, 1999), Caucasus with a mass balance of Djankuat glacier of $-0.13\,\mathrm{m\,w.e.\,a^{-1}}$ from 1966/67 to 2002/03 (Shahgedanova et al., 2007), Penny Ice Cap in the Canadian Arctic with a mass balance of the Southern Canadian Arctic Archipelago of $-0.57\,\mathrm{m\,w.e.\,a^{-1}}$ as calculated from mass losses derived by Gardner et al. (2011) for the 2004–2009 period, Alaska Range with a mass balance of $-0.30\,\mathrm{m\,w.e.\,a^{-1}}$ from 1953 to 2004 (Berthier et al., 2010), and Southern Patagonia Ice Field with a mass balance of $-0.93\,\mathrm{m\,w.e.\,a^{-1}}$ as calculated from elevation changes by Rignot et al. (2003) for the period 1975 to 2000. Other mass balance estimates also exist for some of these regions, but we choose the most recent estimates. In addition we also select Karakoram in Himalaya, where modelled climate data indicate positive mass balance over the last decades, and measured glacier speed increases at Baltoro glacier are assumed to be associated with this mass surplus (Quincey et al., 2009).

The aim of this study is to test if, and to what degree, glacier speeds have decreased on regional scales due to negative mass balance. Such a relationship is well expected, but it has never been observed on regional scales before. It has been observed for individual glaciers using ground observations (Haefeli, 1970; Span and Kuhn, 2003; Vincent et al., 2009), but also the opposite has been observed (Vincent et al., 2000). Because glaciers may behave very differently even though they experience the same climatic conditions, the relationship between mass balance and speed should not only be studied for individual glaciers, but also for entire regions.

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2 Methods

All previous studies that have investigated glacier velocities on regional scales using optical images have used ASTER images. In this study however, we use Landsat images, because they have several advantages compared to ASTER images in studies like the present. One Landsat image covers an area of 183 km by 170 km for ETM+, 185 km by 172 km for TM and 185 km by 185 km for MSS, whereas one ASTER image covers an area of only 60 km by 60 km. The Landsat series also extends long back in time, to 1982 with 30 m spatial resolution and to 1972 to 1982 with 68 m by 83 m spatial resolution. This makes it possible to study long-term velocity changes. ASTER only extends back to 1999. (We should however note that it is also possible to combine ASTER and Landsat data in the kind of study performed here, Kääb et al., 2005b). Landsat images are also used in other studies of global glacier changes, like Global Land Ice Measurements from Space (GLIMS) (Bishop et al., 2004; Kargel et al., 2005; Raup et al., 2007), GlobGlacier and Glacier_CCI. The use of Landsat data for glacier velocity measurements thus ensures a consistency in source data for the various glacier parameters derived, and a larger combined automation potential. The spatial resolution is 15 m for both panchromatic Landsat images after 1999 and visible and near-infrared ASTER images. Landsat images are available at no cost through the US Geological Survey (USGS), and ASTER images are available at no cost for scientific users. The disadvantage with Landsat images however, is subpixel noise created by attitude variations. Lee et al. (2004) found that the image-to-image registration accuracy was better than the requirement of 7.3 m, and that the average was at about 5 m for the ETM+ sensor. For the TM sensor the accuracy is approximately 6 m (Storey and Choate, 2004). This noise is impossible to model because TM and ETM+ are whisk-broom systems, and therefore the accuracy of the image-to-image registration reduces to this level. For most glaciological studies this is an acceptable accuracy because the glacier displacements over the time period that the glacier features are preserved by far exceed this noise level. The attitude variations of ASTER images can

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be modelled and removed, as is done in the COSI-Corr matching software, and therefore displacements derived using ASTER can be more accurate than displacements derived using Landsat. In consideration of the above aspects and our primary goal, worldwide decadal-scale glacier velocity changes, we use images from both Landsat TM and Landsat ETM+, depending on the availability of data. The images used in this study are listed in Table 1.

We mainly use cross-correlation operated in the frequency domain on orientation images (CCF-O), a method developed by Fitch et al. (2002), to derive glacier displacements in this study. This method was one of the methods that performed the best on most glacier surfaces in a worldwide evaluation study by Heid and Kääb (2011). COSI-Corr performed slightly better in general, especially in areas with low visual contrast, but COSI-Corr cannot match striped Landsat images. Landsat7 images are striped from May 2003 and onwards because of a failure of the scan line corrector (SLC-off). To also be able to use these striped images we select CCF-O instead of COSI-Corr. However, in Caucasus we use normalized cross-correlation (NCC) because this method performs the best on smaller glaciers with good visual contrast (Heid and Kääb, 2011).

First we derive orientation images from the original images. Taking f as the image at time $t = 1$ and g as the image at time $t = 2$, the orientation images f_o and g_o are created from

$$f_o(x,y) = \mathrm{sgn}\left(\frac{\partial f(x,y)}{\partial x} + i\frac{\partial f(x,y)}{\partial y}\right) \tag{1}$$

$$g_o(x,y) = \mathrm{sgn}\left(\frac{\partial g(x,y)}{\partial x} + i\frac{\partial g(x,y)}{\partial y}\right) \tag{2}$$

$$\text{where } \mathrm{sgn}(x) = \begin{cases} 0 & \text{if } |x| = 0 \\ \frac{x}{|x|} & \text{otherwise} \end{cases} \tag{3}$$

where sgn is the signum function and i is the complex imaginary unit. The new images f_o and g_o are complex and hence consist of one real and one imaginary part, where the intensity differences in the x direction represent the real matrix and the intensity differences in the y direction represent the imaginary matrix. These orientation images are then matched using cross-correlation operated in the frequency domain. The cross-correlation surface CC is given by

$$\mathrm{CC}(i,j) = \mathrm{IFFT}\left(\frac{F_o(u,v)G_o^*(u,v)}{|F_o(u,v)G_o^*(u,v)|}\right). \quad (4)$$

The peak of the cross-correlation surface indicates the displacement. Subpixel displacements are derived by fitting orthogonal parabolic functions to the correlation surface. Subpixel displacements in the x direction dx and in the y direction dy are found using

$$dx = \frac{P(x_m+1,y_m)-P(x_m-1,y_m)}{2(2P(x_m,y_m)-P(x_m+1,y_m)-P(x_m-1,y_m))} \quad (5)$$

$$dy = \frac{P(x_m,y_m+1)-P(x_m,y_m-1)}{2(2P(x_m,y_m)-P(x_m,y_m+1)-P(x_m,y_m-1))} \quad (6)$$

where $P(x_m,y_m)$ is the maximum correlation value. The parabolic function is therefore fitted using the two nearest neighbors.

For each of the five study areas we use a small but representative section of the Landsat images to find the optimal matching window size. Applying this selection procedure on entire Landsat images would be very time consuming due to the ETM+ image size of about 15 000 pixels by 17 000 pixels. The size of the small test sections used is 30 km by 30 km. Different window sizes are tested on this section to find a window size that optimizes the matching results. The matching result is considered to be optimized when assumed correct matches are obtained over most of the glacierized areas, but without increasing the window size more than necessary. This is to avoid much deformation in one window (Debella-Gilo and Kääb, 2011c). The spacing between the matching windows is half the window size, which means that the matchings are not completely independent. The size of the matching windows used is given in Table 2.

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Following basic glacier physics, in particular stress transfer, we choose to filter the obtained vectors depending on the neighboring vectors, so that vectors are assumed correct if they agree to a certain extent with their neighboring vectors. First, all vectors outside glacierized areas are removed using digital glacier outlines from GLIMS if available or we digitize such outlines from Landsat images. Then the assumed real maximum displacement is found by manually investigating the vectors. All vectors larger than the assumed real maximum displacement are removed. Using only the remaining vectors, the displacement field in both x and y direction is filtered using a 3 by 3 mean low-pass filter. Individual original vectors that deviate more than a certain threshold from this low-pass filtered displacement field are removed (Heid and Kääb, 2011). The threshold varies between the different areas depending on the displacement variations within the areas. Such filtering is not conducted in Caucasus and Patagonia because of the few correct matches derived in these areas. Table 2 shows the different thresholds.

For Pamir, Alaska Range and Karakoram the velocity fields derived are dense enough for comparing velocities derived for points closest to the centerline. However, for Caucasus, Penny Ice Cap and Patagonia the derived velocity fields are more patchy, and therefore also points further away from the centerline are accepted. In all cases the automatically derived results are checked manually in the end and points with mismatches in one or both of the two periods are removed. Thus, only points with accepted matches in both periods are used for computing velocity changes.

The accuracy of the measurements is in theory determined by the image-to-image registration accuracy of the Landsat images and the accuracy of the matching method. But, because the accuracy of the matching method is much smaller than the image-to-image registration accuracy, the accuracy is dominated by the image-to-image registration accuracy (Heid and Kääb, 2011). The uncertainty of single measurements is ± 5 m for ETM+ (Lee et al., 2004) and ± 6 m for TM (Storey and Choate, 2004), whereas the accuracy of the matching method is around 1/10 of a pixel (Heid and Kääb, 2011). We matched stable ground in all of the image pairs, and for all image pairs the root mean square error (RMSE) was between 1.8 m and 5.7 m. For comparison of two different displacement measurements, the uncertainty will be ± 8 m for ETM+ and ± 9 m for TM using root sum square (RSS). Since time spans are about one year, but in some cases slightly shorter, speed changes of more than ± 10 m a^{-1} are considered significant speed changes in this study.

3 Results

Changes in glacier speed in the areas with negative mass balance are derived for the 2000/2001–2009/2010 period for Pamir, the 1986/1987–2010/2011 period for Caucasus, the 1985/1987–2009/2010 period for Penny Ice Cap, the 1986/1987–2009/2010 period for Alaska Range, and the 1984/1986–2001/2002 period for Patagonia. Speed changes from the first to the second period are shown in Figs. 1 and 2 and are also summed up in Table 3. We compute the mean speeds and their changes from the means of each individual glacier, not from all measurements directly. This normalization is necessary because some glaciers are large or have good visual contrast and allow thus for many measurements, whereas others do not. However, it is important to notice that the numbers in Table 3 are not area averages since not all glaciers and all parts of glaciers are covered. Thus, the numbers from our study are indicative for speed changes but do not quantitatively reflect overall ice flux changes. The largest reduction in speed per decade is found in Pamir where the speed decreased by 43 % per decade. Caucasus has the smallest reduction in speed with only 8 % reduction per decade. Decadal reduction in glacier speed is calculated by simply dividing total change through number of decades, not as compound interest due to the short time intervals involved.

In Pamir we derive speed changes for parts of 50 glaciers. The majority of the glaciers reduced their speed or showed no significant speed changes over the time period, but two glaciers, Bivachnyy and Grum-Grzhimailo, also increased their speeds (Fig. 1a). Pamir is a region with surging glaciers, hence also surge activities potentially influence the results. In total the speed decrease is of about 39 % or 43 % per decade.

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In Caucasus we derive speed changes for parts of 16 glaciers. Most glaciers reduced their speed over the time period (Fig. 1b), but the largest glacier in the area, Bezengi glacier, increased its speed over large parts of the glacier. In total, the areas we map show a general decrease in glacier speed of about 19 % over the time period, which translates to about 8 % per decade.

Speed changes are derived for parts of 12 of the outlet glaciers of Penny Ice Cap. Generally all glaciers decreased their velocity from the first period to the second (Fig. 1c). The total speed decrease over the areas we map is about 59 % or 25 % per decade.

The matching in the Alaska Range gives us speed changes for parts of 9 glaciers. All but one glacier, Ruth Glacier, have reduced their speed or had constant speed over the time period (Fig. 1d). Also this is an area with surging glaciers. In total the speed decrease is about 26 %, or 11 % per decade.

In Patagonia speed changes are derived for 10 of the northern outlet glaciers of the Southern Patagonia Ice Field. All the outlet glaciers that we map have reduced their speed over the time period (Fig. 1e), and the total percentage of speed reduction is 34 %, or 20 % per decade.

We also derive changes in glacier speed for Karakoram for the 2001/2002–2009/2010 period (east) and for the 2000/2001–2009/2010 period (west) (Fig. 3). Glaciers in this area are assumed to have had a positive mass balance over the last years (Quincey et al., 2009) and the Karakoram area is also known for its many surging glaciers (Hewitt, 1969, 2007; Copland et al., 2009).

As Fig. 3 shows, the pattern of velocity changes in Karakoram is complex. In the east, glaciers are mainly increasing their speeds, but the difference in speed between the first and the second period is generally less than 25 $m\,a^{-1}$. Two exceptions are Stanghan glacier and Skamri glacier, which have low speeds in the first period and very high speeds in the second period. In the west, the speed changes are dramatic for glaciers flowing into the Shimshal valley and also for Khiang glacier and Batura glacier. However, there is no clear pattern in the velocity changes, and both accelerating and

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decelerating glaciers are found. In Shimshal valley the speeds are high in both periods, but they are extremely high in one of the periods. Khiang glacier has high speeds in the first period, but in the second period the speed is close to zero. Batura glacier has high speeds in both periods, but the speed is increasing from the first to the second period.

4 Discussion

All the glacier regions with negative mass balance that we investigate in this study show a clear sign of glacier deceleration on a regional scale. This indicates that indeed less ice mass is transported down the glaciers so that the glaciers are thinning and retreating in their lower parts as a response to the negative mass balance. However, there is a lag expected between changes in mass balance and changes in glacier speeds due to the response time of glaciers (Johannesson et al., 1989). The response time is related to the altitudinal mass balance gradient, the mean surface slope of the glacier and the length of the glacier (Oerlemans, 2005).

It is not possible to see a clear correlation between the magnitude of the mass balance in a study region and the percentage speed change on a regional level. This might be due to several factors. Firstly, and most importantly, it can be due to the response times of the glaciers in the different regions. The regions are different when it comes to the factors influencing the response time, hence very different response times must be expected. Secondly, the mass balance estimates and the speed reduction estimates might not be representative for the same regions. Speed differences are not derived for all parts of the glaciers or for all glaciers within one region, and mass balance is sometimes derived for single glaciers within the regions or sometimes for larger regions than what we have investigated. Thirdly, the mass balance estimates and the speed change estimates are from different time periods. Fourthly, glaciers could have changed their amount and way of sliding, i.e. their flow mode, independently of mass balance changes. Or similar, surge-type activities, at lower magnitudes

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than full surges, though, may have influenced our measurements. Fifthly and finally, one should have in mind that our measurements represent speed changes between two annual periods, and not necessary steady changes in ice flux on a decadal scale.

Some of the glaciers are accelerating from the first to the second period. In Pamir two glaciers are accelerating, in Caucasus one glacier is accelerating and one glacier is also accelerating in the Alaska Range. Both Pamir and the Alaska Range contain surging glaciers. It is therefore not surprising that some glaciers in these areas are accelerating. The Bivachnyy Glacier in Northwestern Pamir is clearly a surge type glacier in its quiescent phase in the first period, due to velocities close to zero. In the second period this glacier is moving much faster with maximum speed of about 100 m a^{-1}. These speeds probably reflect a surge or surge-type movement. Looped moraines on this glacier as visible in the satellite images also confirm that it is a surge-type glacier. The Grum-Grzhimailo Glacier to the southeast in Pamir and the accelerating glacier in Alaska Range, Ruth Glacier, cannot be defined as surge type glaciers from the velocity measurements obtained in this study. These glaciers have speeds of more than 100 m a^{-1} in both periods, and in addition no looped moraines can be seen in the satellite images. It is however likely that it is flow instabilities that are causing these increased speeds since the glaciers are situated in areas containing surging glaciers and because they are behaving differently from their neighbouring glaciers. The accelerating glacier in Caucasus, Bezengi Glacier, can possibly be accelerating as a reaction to positive mass balance values. Mean mass balance here was close to zero for the period 1966/67 to 2002/03 (Shahgedanova et al., 2007), but the mass balance measurements were only done on one glacier, the Djankuat Glacier, so mass balance might have been positive for Bezengi Glacier.

Although Penny Ice Cap and Patagonia have a smaller decrease in glacier speed per decade than Pamir, these are the two areas that show the most homogeneous speed decrease from the first period to the second. No glacier in these two areas accelerates, and in Patagonia almost all compared points show a speed decrease of more than 20 m a^{-1} from the first to the second period. This is probably because all

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investigated glaciers in these two areas are dynamically stable and hence only have velocity variations that can be attributed to changes in mass balance.

The moderate increase in glacier speeds in Eastern Karakoram indicates that these glaciers are increasing their speeds as a response to the positive mass balance in this area. Quincey et al. (2009) found that Baltoro accelerated due to positive mass balance, and the present study shows that this is also the case for Siachen Glacier. Staghan Glacier and Skamri Glacier are clearly surge-type glaciers in their quiescent phase in the first period due to their low speeds. In the second period the glaciers are surging according to derived speeds of more than 200 m a^{-1} and also large areas where the speed cannot be measured probably due to very high speeds and much surface transformation.

Many of the glaciers flowing into the Shimshal valley are glaciers with flow instabilities. They cannot be characterized as surge type glaciers from the speed changes derived in this study. This is because they have large speeds in both periods, hence sliding is clearly an important component of the surface speed although the velocities are lower than in the other period. A previous study has speculated that many glaciers in the Karakoram have flow instabilities instead of being of classical surge type (Williams and Ferrigno, 2010). The results in the present study for glaciers flowing into Shimshal valley support this.

Khiang Glacier was in the first period moving more than 100 m a^{-1}. In the second period its speed was close to zero. This glacier has not been identified as a surging glacier before. A tributary of Batura Glacier in the west is surging in the last period, influencing also the speed of Batura Glacier in the confluence zone.

The velocity measurements obtained here indicate that glaciers in Karakoram behave differently depending on location. Glaciers in the east seem to by dynamically stable and their speed changes are linked to changes in mass balance. This is also supported by the very few observations of glacier surges in this area, and few looped moraines. The Central North Karakoram probably contains many surging glaciers because of the very low speeds that are measured in this area. This indicates that these

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are surging glaciers in their quiescent phase. Many of these glaciers have also been identified as surging glaciers in previous studies (Hewitt, 1969, 2007; Copland et al., 2009). The area in northwest contains many dynamically instable glaciers that cannot be defined as surging glaciers in the classical sense. This is because their speed is always high, and therefore sliding seems very important at all times. This area also contains some classical surging glaciers.

5 Conclusions and perspectives

In this study we derived speed changes using repeat optical satellite images for five large glacier regions of the world with negative mass balance: Pamir, Caucasus, Penny Ice Cap, Alaska Range and Patagonia. We also derived speed changes for Karakoram, which is an area with positive mass balance and that contains a large number of surging glaciers. In general, all the five regions with negative mass balance had a mean speed decrease in mapped areas from the first period to the second period. Glaciers in Pamir reduced their speed by 43 % per decade, glaciers in Caucasus by 8 % per decade, outlet glaciers from Penny Ice Cap by 25 % per decade, glaciers in the Alaska Range by 11 % per decade and outlet glaciers from the Southern Patagonia Ice Field by 20 % per decade.

On regional scales and over longer time periods, the glacier speeds are expected to decrease because less mass accumulates and therefore also less mass will be transported down to lower elevations. We have shown that this regional speed decrease is taking place. However, we could not observe a relationship between magnitude of negative mass balance and percent speed decrease. This may be because the response time of glaciers is different from area to area, and within the areas, and due to other reasons such as the uncertain representativeness of our velocity measurements. Glaciers in Karakoram generally increased their speed due to the positive mass balance, but the speed changes here are heavily influenced by the dynamic instabilities in this area.

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Our study opens up for a range of other analyses based on regional or worldwide glacier velocity measurements as were demonstrated here. For instance, it seems possible to roughly estimate the response time of glaciers from inventory parameters (Haeberli and Hoelzle, 1995), and investigate their correlation with speed changes and mass balance measurements. Velocity measurements can be correlated against glacier inventory parameters such as length, area and hypsometry. Glacier velocities can also be used to estimate erosion rates or mechanisms (Scherler et al., 2011b) and transport times (Casey et al., 2011) and thus to contribute towards better understanding of glacial landscape development. On the more applied side, widespread decrease in glacier speed will increase the probability and speed of glacier lake development in areas prone to such lakes, because ice supply is one of the dominant factors in lake development and growth. Studies of speed change can help to point out areas where glacier lakes can develop or the growth of existing ones is expected (Kääb et al., 2005a; Bolch et al., 2008; Quincey et al., 2007).

Now that it is demonstrated to be feasible not just to focus velocity measurements on specific glaciers or smaller glacier regions, more effort should be put into deriving glacier velocities globally. This study shows that deriving glacier velocities for large regions or even on a global scale can give valuable insights to glaciers' dynamic climate change response and to glacier flow instabilities. It also shows that there is a potential to understand the importance of glacier sliding and deformation on regional scales better by investigating speed changes over time and the spatial structure of velocities.

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Table 1. Overview of the image pairs used in this study.

Area	Sensor	Path/Row	Date image $t=1$ period 1	Date image $t=2$ period 1	Date image $t=1$ period 2	Date image $t=2$ period 2
Pamir	ETM+/TM	151/33	24 Aug 2000	26 Jul 2001	9 Aug 2009	27 Jul 2010
Caucasus	TM	171/30	6 Aug 1986	26 Sep 1987	8 Aug 2010	11 Aug 2011
Penny Ice Cap	TM	18/13	19 Aug 1985	24 Jul 1987	21 Aug 2009	7 Jul 2010
Alaska Range	TM	70/16	15 Jun 1986	21 Aug 1987	20 Aug 2010	6 Jul 2011
Patagonia	TM	231/94	26 Dec 1984	14 Jan 1986	20 Mar 2001	18 Jan 2002
Karakoram east	ETM+	148/35	16 Jun 2000	21 Jul 2001	28 Aug 2009	31 Aug 2010
Karakoram west	ETM+	149/35	29 Aug 2001	16 Aug 2002	20 Sep 2009	22 Aug 2010

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Table 2. Matching window sizes and filtering thresholds in the different areas.

Area	Matching window m	Filtering threshold m
Pamir	240	± 105
Caucasus	120	–
Penny Ice Cap	240	± 90
Alaska Range	480	± 120
Patagonia	480	–
Karakoram	240	± 45

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Table 3. Speed change for each area.

Area	Mean speed change $m\,a^{-1}$	Mean speed 1. period $m\,a^{-1}$	Percent speed change	Percent speed change per decade $decade^{-1}$	Number of points	Number of glaciers
Pamir	−17.0	45.8	−39 %	−43 %	3148	50
Caucasus	−4.9	25.7	−19 %	−8 %	1057	16
Penny	−12.6	21.3	−59 %	−25 %	471	12
Alaska Range	−15.9	61.2	−26 %	−11 %	1018	9
Patagonia	−85.3	248.6	−34 %	−20 %	85	10

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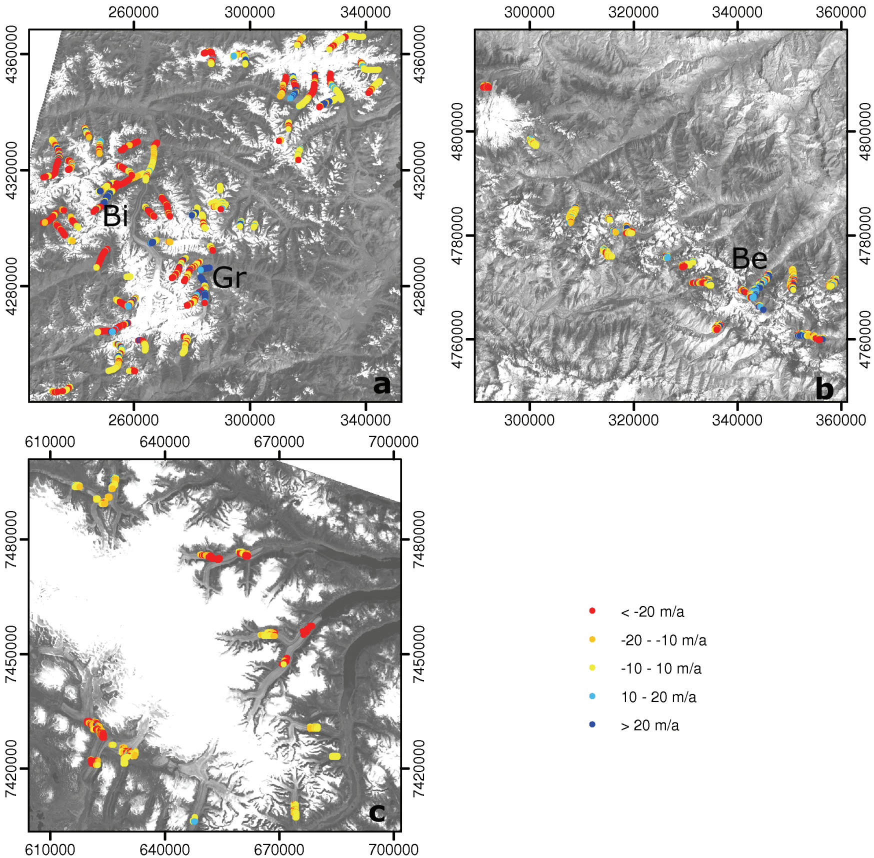

Fig. 1. Glacier speed changes between the two periods for **(a)** Pamir, **(b)** Caucasus and **(c)** Penny Ice Cap. Negative values indicate lower speeds in the second period. Changes between $-10\,\mathrm{m\,a^{-1}}$ and $10\,\mathrm{m\,a^{-1}}$ are insignificant. Bi indicates Bivachnyy, Gr indicates Grum-Grzhimailo and Be indicates Bezengi.

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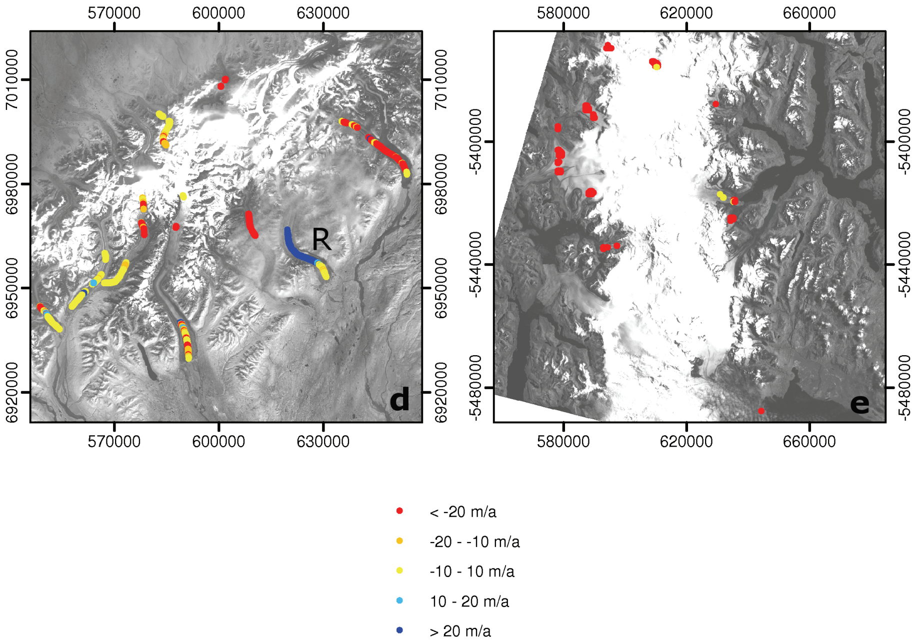

Fig. 1. Glacier speed changes between the two periods for **(d)** Alaska Range and **(e)** Patagonia. Negative values indicate lower speeds in the second period. Changes between $-10\,\mathrm{m\,a^{-1}}$ and $10\,\mathrm{m\,a^{-1}}$ are insignificant. R indicates Ruth Glacier.

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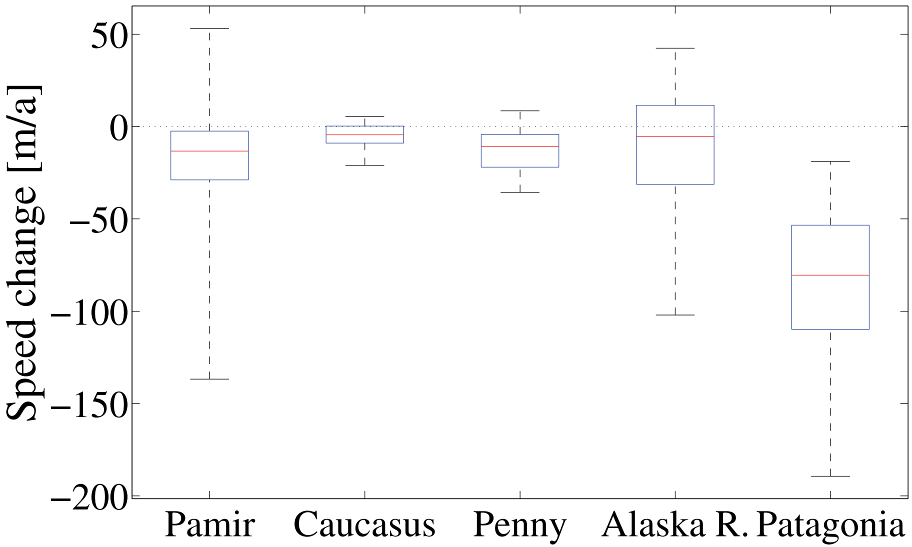

Fig. 2. Box plot showing the speed change of individual glaciers from the first to the second period for the five different regions. The box outline indicates the 25th percentile and the 75th percentile. The dotted bars indicate the range of the speed changes. Negative values indicate lower speeds in the second period.

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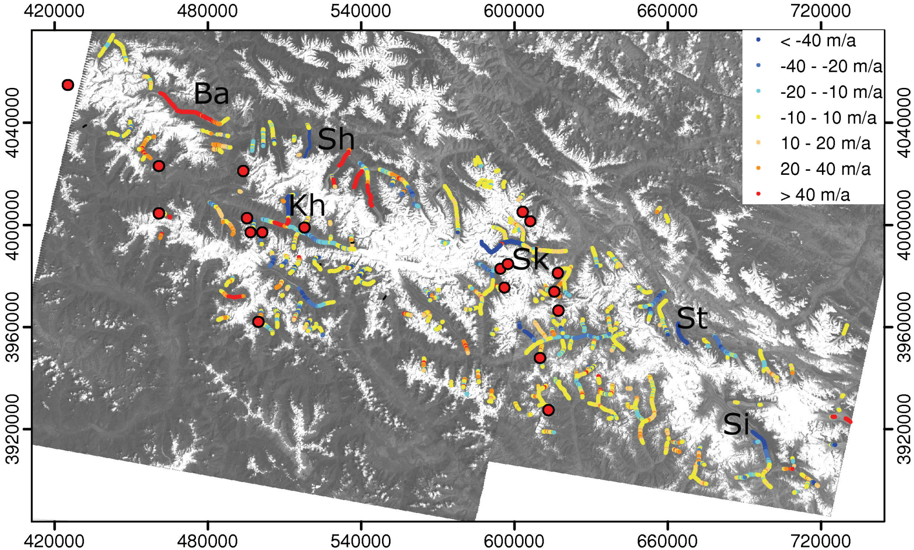

Fig. 3. Differences in centerline speed in Karakoram between the two periods 2001–2002 (east)/2000–2001 (west) and 2009–2010. Negative values indicate lower speeds in the last period. Changes between $-10\,\mathrm{m\,a^{-1}}$ and $10\,\mathrm{m\,a^{-1}}$ are insignificant. Note that the scale is different compared to Fig. 1. The large red circles indicate glaciers that are known to surge (Hewitt, 1969, 2007; Copland et al., 2009). Ba indicates Batura, Sh indicates Shimshal valley, Kh indicates Khiang, Sk indicates Skamri, St indicates Stanghan and Si indicates Siachen.

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