The Cryosphere

Repeat optical satellite images reveal widespread and long term decrease in land-terminating glacier speeds

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Abstract. By matching of repeat optical satellite images it is 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 over the last decades decreased their velocity at an average rate per decade of: 43 % in the Pamir, 8 % in the Caucasus, 25 % on Penny Ice Cap, 11 % in the Alaska Range and 20 % in Patagonia. Glaciers in Karakoram have generally increased their speeds, but surging glaciers and glaciers with flow instabilities are most prominent in this area. Therefore the calculated average speed change is not representative for 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), where some of the terms are solved using Fast Fourier Transform (FFT). 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 Ladstädter, 2003; Debella-Gilo and Kääb, 2011b), and lately methods correlating only in the frequency domain 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., 2011a,b; McFadden et al., 2011). However, much focus has lately been 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, 2012; Scherler et al., 2008) and also on comparing image matching techniques to find the methods that produce best results for glaciers (Heid and Kääb, 2012). It is therefore 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.

For a steady-state glacier, the mass flux through a cross-section equals the mass balance upstream of the cross-section. In negative mass balance regimes, the ice fluxes will decrease to adjust. 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, Caucasus, Penny Ice Cap, Alaska Range and Southern Patagonia Ice Field (Fig. 1). The mass balances of these regions are listed in Table 1. 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 glaciers are assumed to have had a positive mass balance over the last years (Hewitt, 2005), and measured glacier speed increases at Baltoro glacier are assumed to be associated with this mass surplus (Quincey et al., 2009a). The Karakoram area is also known for its many surging glaciers (Hewitt, 1969, 2007; Copland et al., 2009; Quincey et al., 2011; Copland et al., 2011).

The glaciers in the studied regions are mainly alpine and land-terminating, and they are influenced by different climatic conditions. Glaciers on the southern side of the Alaska Range experience a maritime climate, as well as glaciers of the western sides of the Southern Patagonia Ice Field. The other regions have a more continental climate. We can only select areas were it is possible to derive yearly speeds for two periods separated by more than a decade, and hence the availability of Landsat images also influences the selection. Karakoram is chosen because Baltoro glacier has increased its speed during the last years (Quincey et al., 2009a) possibly due to positive mass balance, and we therefore want to investigate whether this is also the case for other glaciers in this region. In addition we want to look into the temporal and spatial variability in glacier speeds in Karakoram.

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. Quincey et al. (2009b) derived speeds for six glaciers in the Himalaya region between 1992 and 2002, but these data show no clear sign of a reduction in speed with time. A reduction in speed in areas with negative mass balance has been observed for individual glaciers using ground observations (Haefeli, 1970; Span and Kuhn, 2003; Vincent et al., 2009), but also increase in speed in areas with negative mass balance 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.

2 Methods

Most previous studies that have investigated glacier velocities on regional scales using optical images have used ASTER images. One exception is McFadden et al. (2011), who also used Landsat images. We use Landsat images for this study because of the advantages given below. Sensor specifications are listed in Table 2. The main advantages of Landsat are that one Landsat image covers a 9-fold larger area than an ASTER image, and that they extend back to 1972. The latter makes it possible to study long-term velocity changes. 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. Landsat images are available at no cost through the US Geological Survey (USGS).

The disadvantage with Landsat images however, is sub-pixel noise created by attitude variations. Lee et al. (2004) found that the image-to-image registration accuracy was better than the Landsat-7 image-to-image systematic product accuracy 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 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, regional 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 3.

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 (2012). COSI-Corr performed slightly better in general, especially in areas with low visual contrast, but COSI-Corr cannot match striped Landsat images. Landsat-7 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, 2012).

Fig. 1. Location of the six studied regions.

Table 1. Mass balance estimates for the six regions.

Area	Mass balance (m w.e. a^{-1})	Period	Area of mass balance estimate	Source
Pamir	−0.53	1980–1997	Abramov	WGMS (1999)
Caucasus	−0.13	1966/1967–2002/2003	Djankuat	Shahgedanova et al. (2007)
Penny Ice Cap	−0.57	2004–2009	Southern Canadian Arctic Archipelago	Gardner et al. (2011)
Alaska Range	−0.30	1953–2004	Alaska Range	Berthier et al. (2010)
Patagonia	−0.93	1975–2000	Southern Patagonia Ice Field	Rignot et al. (2003)
Karakoram	−	−	−	−

Table 2. Landsat and ASTER sensor specifications.

Sensor	Spatial resolution (m)	Image size (km)	Period of operation
Landsat ETM+	15	183 × 170	1999–present
Landsat TM	30	185 × 172	1982–present
Landsat MSS	68 × 83	185 × 185	1972–2001
ASTER	15	60 × 60	1999–present

When using orientation correlation, we first 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

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

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

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

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

$$\text{CC}(i,j) = \text{IFFT}\left(F_o(u,v)G_o^*(u,v)\right). \tag{4}$$

The peak of the cross-correlation surface indicates the displacement. Subpixel displacements are derived by fitting orthogonal parabolic functions to the correlation surface.

For each of the six 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

Table 3. Overview of the image pairs used in this study. Path/Row refers to the Landsat satellite orbit coordinate system.

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

Table 4. Matching window sizes and filtering thresholds in the different areas.

Area	Matching window (m)	Filtering threshold (m)
Pamir	480	± 105
Caucasus	240	–
Penny Ice Cap	480	± 90
Alaska Range	480	± 120
Patagonia	960	–
Karakoram	480	± 45

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 4.

Using specified minimum smoothness of the glacier flow field, we filter the vectors based on comparison with their neighbors. First, all vectors outside glacierized areas are removed using digital glacier outlines from GLIMS if available or we digitize such outlines from Landsat images. 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, 2012). The threshold varies between the different areas depending on the displacement variations within the areas. Table 4 shows the different thresholds. The low-pass filtered displacement field is only used to

filter the raw displacement field, and not for the final speed comparison. Automatic filtering is not conducted in Caucasus and Patagonia because of the few correct matches derived in these areas.

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 by removing points with mismatches in one or both of the two periods. 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 quality of the orthorectification, the image-to-image registration accuracy of the Landsat images, and the accuracy of the matching method. Orthorectification may introduce horizontal shifts that are not due to displacement but due to errors in the orthorectification. Such errors can stem from wrong information about the camera position, look direction or lens distortions, atmospheric effects, or errors in the digital elevation model (DEM). Errors in the DEM will influence all images obtained from the same point in the same way. Therefore, in this study where the two matched images are obtained from the same path and row, DEM errors create only minor errors in the derived velocities. If the same DEM is used to orthorectify images from different times and the glacier surface elevation changes between image acquisitions, this can create horizontal shifts that are not due to displacement but due to change in elevation. This effect increases the further off nadir the image point is, and for the outer parts of Landsat images the glacier surface has to change its elevation by 39 m over the time period between two acquisitions to change the horizontal position 1/3 of a 15 m pixel. In image matching such large changes in elevation will also lead to surface decorrelation, and it will not be possible to obtain correct matches. The uncertainty caused by the image-to-image registration accuracy of single

measurements is ±5 m for ETM+ (Lee et al., 2004) and ±6 m for TM (Storey and Choate, 2004). The accuracy of the matching method is around 1/10 of a pixel (Heid and Kääb, 2012). We also 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 $\pm 10\,\mathrm{m\,a^{-1}}$ are considered significant speed changes in this study.

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 thus allow for many measurements, whereas others do not. However, it is important to notice that the numbers are not area averages since not all glaciers and all parts of glaciers are covered. Deriving glacier velocities using image matching depends on visual contrast in the images. Generally, measurements are therefore restricted to the ablation area and crevassed parts of the accumulation area. Thus, the numbers from our study are indicative for speed changes but do not quantitatively reflect overall ice flux changes. 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.

3 Results

Changes in glacier speeds 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, the 1984/1986–2001/2002 period for Patagonia, the 2001/2002–2009/2010 period for Karakoram east, and the 2000/2001–2009/2010 period for Karakoram west. Speed changes from the first to the second period are shown in Figs. 2, 3 and 4 and are also summed up in Table 5. The glacier elevation and the elevation of the measurements in each region are shown in Table 6. Elevation data are obtained through http://www.viewfinderpanoramas.org, http://eros.usgs.gov and http://www.geobase.ca. 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 of the regions with negative mass balance with only 8 % reduction per decade. Glaciers in Karakoram increased their speeds by 5 % per decade.

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, increased their speeds (Fig. 2a). Pamir is a region with surging glaciers (Dol-

gushin et al., 1963), hence also surge activities potentially influence the results. In total the speed decrease is about 39 %, which translates to 43 % per decade.

In Caucasus we derive speed changes for parts of 16 glaciers. Most glaciers reduced their speed over the time period (Fig. 2b), 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 speed from the first period to the second (Fig. 2c). 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. 2d). Also this is an area with surging glaciers (Post, 1969). 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. 2e), and the total percentage of speed reduction is 34 %, or 20 % per decade.

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 $25\,\mathrm{m\,a^{-1}}$. 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 decelerating glaciers are found. For glaciers 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. This glacier has not been identified as a surging glacier before. Batura glacier has high speeds in both periods, but the speed is increasing from the first to the second period. 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. Overall, glaciers in Karakoram increased their speeds with about 5 % per decade, but as Fig. 4 shows, the variation in this area is considerable and the speed change thus not statistically significant.

In Pamir and on Penny Ice Cap we also investigate speeds in an intermediate period to estimate whether there are marked velocity variations during the main observation period. In Pamir we use images from 4 September 2004 and 7 September 2005, and on Penny Ice Cap we use images from 19 July 1997 and 22 July 1998. In Pamir the speeds
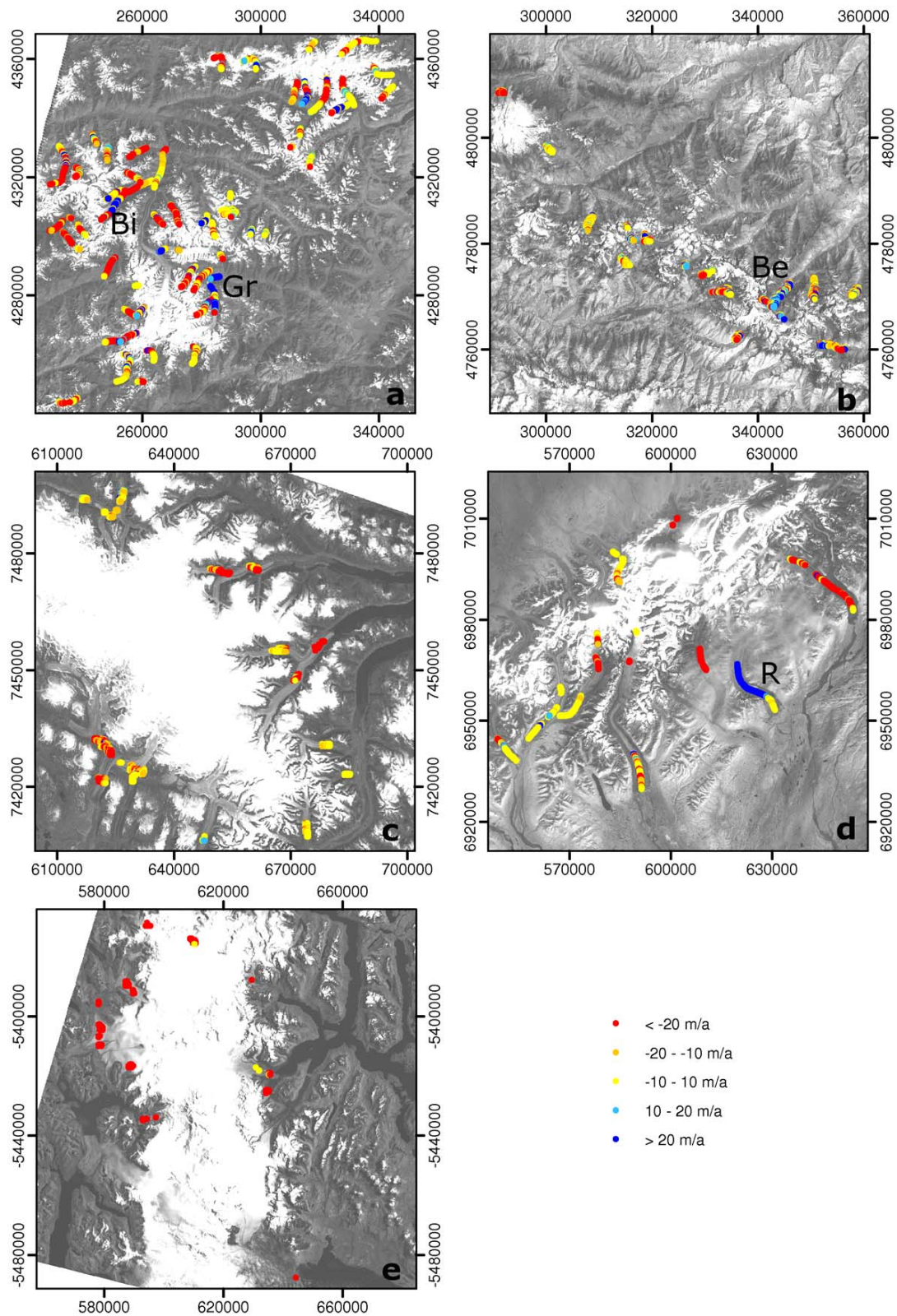
Fig. 2. Glacier speed changes between the two periods for **(a)** Pamir, **(b)** Caucasus, **(c)** Penny Ice Cap, **(d)** Alaska Range and **(e)** Patagonia. Negative values indicate lower speeds in the second period. Changes between $-10\,\mathrm{m\,a^{-1}}$ and $10\,\mathrm{m\,a^{-1}}$ are insignificant. Bi indicates Bivachnyy, Gr indicates Grum-Grzhimailo, Be indicates Bezengi, and R indicates Ruth Glacier.

Table 5. Speed change for each area.

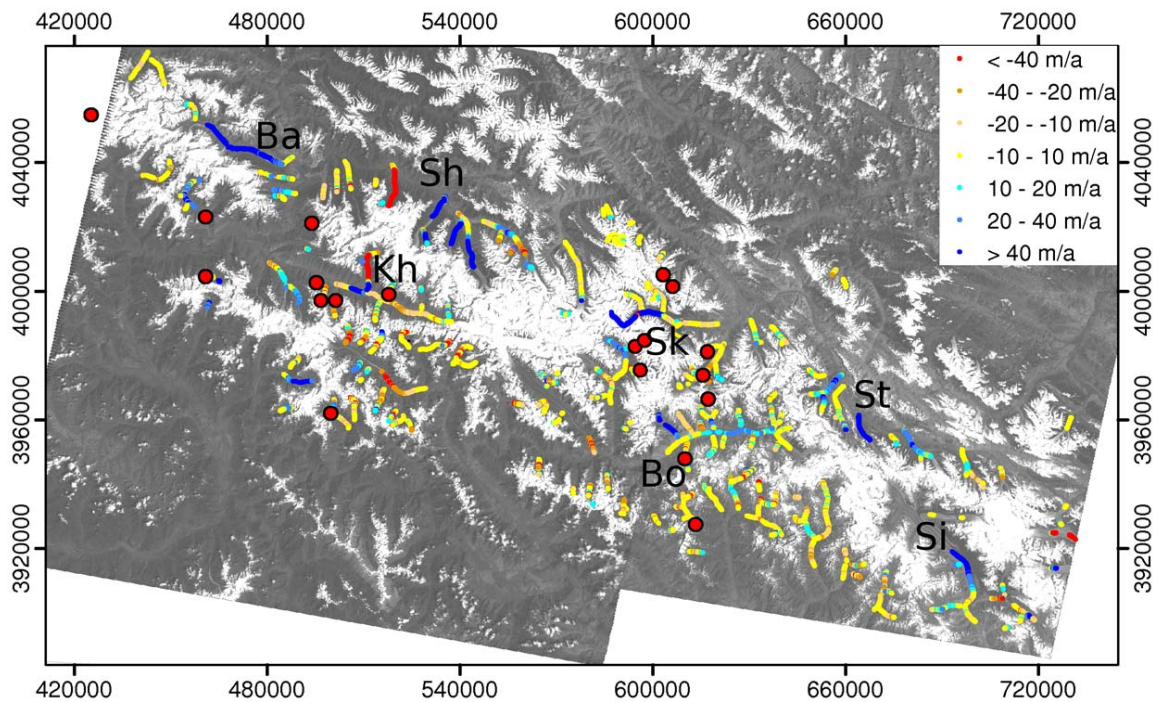| Area	Mean speed change (m a^{-1})	Mean speed 1. period (m a^{-1})	Percent speed change	Percent speed change per decade decade^{-1}	Number of points	Number of glaciers
Pamir	−17.0	45.8	−39 %	−43 %	3148	50
Caucasus	−4.9	25.7	−19 %	−8 %	1057	16
Penny Ice Cap	−11.3	21.3	−53 %	−22 %	471	12
Alaska Range	−15.9	61.2	−26 %	−11 %	1018	9
Patagonia	−85.3	248.6	−34 %	−20 %	85	10
Karakoram	1.9	39.3	5 %	5 %	9370	181

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 m a^{-1} and 10 m a^{-1} are insignificant. Note that the scale is different compared to Fig. 2. The large red circles indicate glaciers that are known to surge (Hewitt, 1969, 2007; Copland et al., 2009). Ba indicates Batura, Bo indicates Baltoro, Sh indicates Shimshal valley, Kh indicates Khiang, Sk indicates Skamri, St indicates Stanghan and Si indicates Siachen.

increase by 4.1 m a^{-1} from 2000–2001 to 2004–2005, and from 2004–2005 to 2009–2010 they decrease by 18.3 m a^{-1}. Only 1873 points are used to derive the changes using the intermediate period in Pamir due to striped Landsat-7 images that reduce the number of correct matches. On Penny Ice Cap the speeds increase by 1.5 m a^{-1} from 1985–1987 to 1997–1998, whereas they decrease by 11.3 m a^{-1} from 1997–1998 to 2009–2010. In this area the same points are being used to derive speed changes using the intermediate period as are being used to derive speed changes without the intermediate 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 suggests that indeed less ice mass is transported down the glaciers so that the glaciers are thinning and receding in their lower parts as a response to the negative mass balance. Glacier mass balance changes can effect the glacier speeds in two ways. First, the local mass balance can change the local glacier thickness and thereby change the local deformation. This happens immediately as
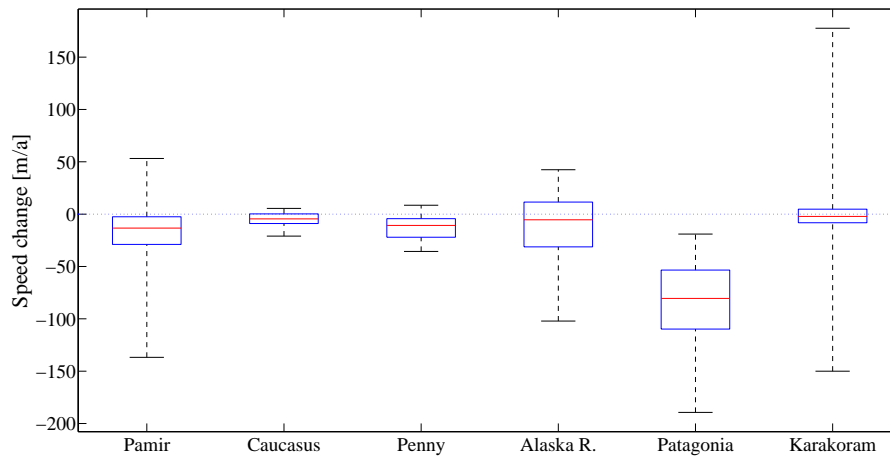
Fig. 4. The speed change of individual glaciers from the first to the second period for the six different regions. The box outline indicates the 25th percentile and the 75th percentile. The dotted bars indicate the range of the speed changes. Negative values indicate lower speeds in the second period.

Table 6. Elevation of glaciers and speed change measurements in each area.

Area	Elevation glaciers (m)	Elevation measurements (m)	Mean elevation glaciers (m)	Mean elevation measurements (m)
Pamir	2583–7490	2670–5171	4779	4244
Caucasus	1755–5629	1755–3809	3551	2677
Penny Ice Cap	14–2135	218–849	1293	600
Alaska Range	185–6188	237–2286	1755	865
Patagonia	0–3600	215–1432	1317	710
Karakoram	2366–8600	2554–6618	5250	4216

the mass balance changes are taking place. Second, mass balance changes upward of a cross-section propagate down-glacier as kinematic waves (Paterson, 1994). The speed of the kinematic wave is greater than the ice speed, and at the wave front the ice flux changes according to the mass balance. The time it takes for a glacier to adjust its front position, and thereby also its front velocity, to a change in its mass balance is called the response time of glaciers (Johannesson et al., 1989). The response time ranges from tens of years for glaciers in warm and wet areas to several thousand years for glaciers in cold and dry climates (Raper and Braithwaite , 2009). However, the reaction time, which is the time it takes before mass balance changes start to effect the terminus, can be very rapid.

As Table 6 shows, the speed change measurements are mainly restricted to the lower parts of the glaciers where the visual contrast favors image matching. When the mass balance is negative the ice flux will be reduced over time because there is less mass to transport. This effect accumulates down-glacier so that the change in ice flux is expected to be small in higher areas of the glaciers and high in lower areas of the glaciers. Because our speed change measurements

mainly cover the ablation area they are not representative for entire glaciers, and speed changes for the entire glacierized areas will be lower than what we have estimated here.

It is not possible to see a clear correlation between the magnitude of the mass balance in a study region (Table 1) and the percentage speed change on a regional level (Table 5). This might be due to several factors. First, 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. Second, 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. Third, the mass balance estimates and the speed change estimates are from different time periods. Fourth, glaciers could have changed their amount of sliding due to changes in water pressure at the bed, which can change independently of mass balance changes. Or similar, surge-type activities, at lower magnitudes than full surges

(Frappé and Clarke, 2007), may have influenced our measurements. Fifth and finally, note that our measurements represent speed changes between two annual periods, and not necessarily steady changes in ice flux on a decadal scale.

Seasonal velocity variations with respect to the image acquisition dates used potentially influence our findings. Wherever possible we therefore tried to find images of a similar point in time within the year. Also, averaging speeds and speed changes over a large number of glaciers will limit the influence of seasonal velocity variations if one assumes that these variations do not happen synchronously over a region. From these considerations follows that the Alaska Range results with the largest difference in acquisition season, in particular between times 1 and 2, and the smallest number of glaciers might potentially be most influenced by velocity seasonality.

Some of the glaciers are accelerating from the first to the second period. 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 $100 \, \mathrm{m\,a^{-1}}$. These speeds probably reflect a surge or surge-type movement. Looped moraines on this glacier are visible in the satellite images and 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 $100 \, \mathrm{m\,a^{-1}}$ in both periods, and in addition no looped moraines can be seen in the satellite images. It is however likely that these changes are more related to surge type activity than to changes in mass balance since the glaciers are situated in areas containing surging glaciers and because they behave differently from their neighboring 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 1966/1967 to 2002/2003 (Shahgedanova et al., 2007), and 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 $20 \, \mathrm{m\,a^{-1}}$ from the first to the second period. This is probably because all 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. (2009a) proposed 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 $200 \, \mathrm{m\,a^{-1}}$ 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.

The velocity measurements obtained here indicate that glaciers in Karakoram behave differently depending on location. Glaciers in the east (around Siachen and Baltoro) seem to be 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 (around Skamri) probably contains many surging glaciers because of the very low speeds that are measured in this area. This indicates that these 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 (around Shimshal) contains many glaciers that vary their speeds considerably between the two periods. However many of them cannot be defined as surging glaciers in the classical sense. This is because the speed is high in both periods, and therefore sliding seems very important at all times. This area also contains some classical surging glaciers.

Both in Pamir and on Penny Ice Cap, where an intermediate period is added to investigate possible speed variations, the speeds are relatively constant in the first period and then negative in the second period. Without representative mass balance series available and without taking glacier response times into consideration a sound interpretation of these temporal variations is not possible. Rather, these results show how intermediate measurements at time-scales less than a decade will be able to refine the observed glacier changes.

5   Conclusions and perspectives

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. We did not have the data to investigate whether there is a quantitative relationship between the magnitude of the negative mass balance and the percent speed decrease. This is 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 with respect to available mass balance data. 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.

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., 2012) 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).

As a future glacier monitoring strategy, annual velocities should be derived every year, preferably for all glaciated regions of the world. Such a monitoring of glacier velocities would allow to study worldwide changes in the velocity fields. Doing this every year would also enable to track significant year-to-year speed variations, which are missed in our study due to the longer time periods between the velocity fields derived.

Now that recent studies have demonstrated that it is 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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