

Recent Interannual Variations of Rockglacier Creep in the European Alps

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Abstract

Recent interannual variations of rockglacier surface motion are compared for 16 landforms monitored for a few years in various parts of the European Alps. Large fluctuations have been observed particularly since 2002. Most investigated rockglaciers have shown a similar behavior whatever their location in the Alpine arc, their size or their velocity. The observed interannual variations appear to be primarily related to external climatic factors rather than to internal characteristics. They are mostly well correlated with mean annual ground surface temperature shifts with a delay of a few months, reflecting the thermal wave propagation deeper into permafrost. Seasonal factors may also play a significant role: a lower intensity of winter ground freezing and/or a larger winter snow accumulation appear to facilitate a higher rate of rockglacier surface motion.

Keywords: European Alps, rockglaciers, creep, surface motion, interannual variations.

Introduction

Rockglaciers act as sediment conveyors in cold periglacial mountain environments. Where a rockglacier is perched on the upper part of a steep valley side, it may be the source of slope instability processes (mainly rock falls and debris flows). Any change in the rate of permafrost creep may modify the delivery of loose materials at the rockglacier snout and is susceptible to affect the frequency, the magnitude and even the type of related slope instabilities (e.g. Roer et al. 2008). In this context and paying regard to the ongoing climate warming trend, there is an increasing request in the densely inhabited European Alps to dispose of precise and up-to-date data documenting the evolution of the high-altitude permafrost environment. In addition to the assessment of longer term (decadal to pluri-decadal) changes affecting rockglaciers dynamics, which can be precisely determined by airborne photogrammetric analysis (Käab et al. 2003), the documentation of the short-term

(interannual and even seasonal) variations is needed. Two decades after the pioneer work on the Gruben rockglacier (Haerberli 1985), the systematic survey of annual velocities has been reinitiated a few years ago by several research teams by means of terrestrial measurements. This paper provides a first comparison of time series that have been measured since 1999/2000 or later on a sample of 16 rockglaciers located in six regions of the Alpine arc.

Background

Mostly located in the lower half of the mountain discontinuous permafrost belt, Alpine rockglaciers are rather warm. They may move relatively fast and are highly sensitive to small temperature changes (Käab et al. 2007).

Three types of temporal variability in surface motion are superimposed on a secular time scale in response to ground surface temperature variations (e.g. Käab et al. 2007, Perruchoud & Delaloye 2007): a decadal to pluri-decadal

trend, interannual variations and a seasonal rhythm. Non-thermally induced changes in rockglacier dynamics (e.g. topography effect) may also influence the creep rate particularly at longer time scales, whereas the infiltration of snowmelt water (Ikeda et al. 2008) and the influence of subpermafrost groundwater (Haeberli 1985, Krainer & Mostler 2006) are also advanced as controlling factors at shorter time intervals. The early measurements on the Gruben rockglacier already indicated that strong short-term velocity variations occur where the permafrost base is above bedrock, and that these variations can be different in lower and upper rock glacier parts, respectively (Haeberli 1985).

Numerous studies carried out in various parts of the Alps (e.g. Roer et al. 2005, Käab et al. 2007, Kaufmann et al. 2007) have shown that the motion of alpine rockglaciers has drastically accelerated since the 1980s, probably in response to an increase in permafrost temperature consecutive to warmer air temperatures. For the past about 15 years however, no clear further warming trend is visible in the borehole temperatures time series on the Murtèl rockglacier in the eastern Swiss Alps (Vonder Mühl et al. 2007).

Seasonal variations have been reported for several rockglaciers (Haeberli 1985, Käab et al. 2003, Hausmann et al. 2007a, Perruchoud & Delaloye 2007), whereas almost constant annual velocities have also been observed (Krainer & Mostler 2006), particularly where permafrost is reaching into bedrock as on the Murtèl rockglacier (Haeberli et al. 1998). Where existing, seasonal fluctuations can be relatively large, reaching up to 50 % from the annual mean. They occur every year more or less at the same time but are not fully synchronous for all rockglaciers. Highest velocities are reached in most cases between summer and early winter, whereas the lowest values are usually observed in spring or early summer. The seasonal increase in velocity can be rapid and connected to the snowmelt process (Perruchoud & Delaloye 2007) or slower and delayed (Käab et al. 2007). On the Muragl rockglacier (eastern Swiss Alps), the annual amplitude of the seasonal rhythm varies significantly, the winter/spring decrease being reduced by warmer winter ground surface temperature (Käab et al. 2007).

Interannual velocity survey and dataset on the observed rockglaciers

Interannual velocities are surveyed by terrestrial measurements (geodetics or real-time kinematic GPS) with accuracy in the mm to cm range. The annual campaign at each rockglacier is carried out as close as possible on the same date - ideally by late summer - in order to avoid an effect of potentially strong seasonal variations on the reliability of the data. Ten to more than 100 marked points covering part or the whole of the rockglacier or disposed along longitudinal and/or transversal profiles are surveyed. The compared value is then the mean horizontal velocity for all moving points with uninterrupted series. This value is considered to be a proxy for the activity of a whole rockglacier, keeping in mind that local differences are frequent for instance in terms of flow rates and amplitudes of annual changes.

The 16 observed rockglaciers (Fig. 1) are located in six distinct regions and are briefly described hereafter and in

Table 1. There is a distance of 600 km between Laurichard (southwest) and Dösen (east) rockglaciers.

Region 1: south-western Alps (France)

Laurichard is a tongue-shaped rockglacier which displays longitudinal furrows in its steepest part and transversal ridges near the edge. Surface velocities have been measured since 1983 (Francou & Reynaud 1992) along a 420 m long longitudinal profile of 17 painted blocks. Mean horizontal velocity over the 1983-2007 period is 0.75 ma^{-1} .

Region 2: western Swiss Alps (Valais)

Mille is a rockglacier looking inactive on morphological criteria (Delaloye 2004), however moving slowly in its steeper lower half (0.02 to 0.05 ma^{-1}).

Aget-Rogneux is a low active back creeping push-moraine located in the Little Ice Age forefield of a small vanished glacier (Lambiel & Delaloye 2004).

Mont-Gelé B and C are two coalescent small rockglaciers. Whereas Mont-Gelé B is moving faster, the deformation of Mont-Gelé C is much reduced despite an apparently higher ice-content (Lambiel & Delaloye 2004).

Tsarmine is a tongue-shaped currently very active rockglacier ending at the top of a steep gully and providing large amounts of loose materials. Local disturbances of the block surface point to a recent drastic acceleration of the rockglacier movement (Lambiel et al. 2008).

The Becs-de-Bosson rockglacier is an active feature consisting of two adjacent lobes. There is no permafrost – and no creep – in the rooting zone of the rockglacier due to the former development of a local glacier during the Little Ice Age. Significant seasonal variations are observed on the whole rockglacier (Perruchoud & Delaloye 2007).

HuHH1 and HuHH3 are two adjacent multilobate rockglaciers situated below cirques. Both landforms are of similar size and showed maximum horizontal velocities up to 4 ma^{-1} in 2003/04 (Roer 2007).

Region 3: northwestern Swiss Alps (Bernese Alps)

Furggentälti is a small, tongue-shaped rockglacier with annual surface displacement currently 5 to 10 times larger than during the period 1960-1974 (Mihajlovic et al. 2008). Seasonal fluctuations were observed in 1998/99.

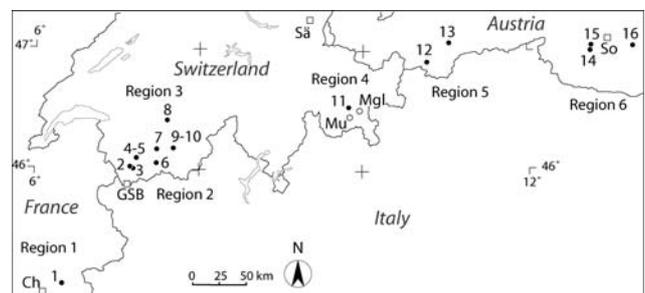


Figure 1. Location of observed rockglaciers (numbers correspond to Table 1). Other cited rockglaciers : Mu: Murtèl; Mgl : Muragl. Regions : 1. south-western Alps (France), 2. western Swiss Alps (Valais), 3. north-western Swiss Alps (Bernese Alps), 4. eastern Swiss Alps (Upper Engadine), 5. western Austrian Alps, 6. central Austrian Alps. Weather stations : Ch: St.-Christophe-en-Oisans; GSB : Grand-St-Bernard; Sä : Säntis; So : Sonnblick.

Table 1. Alpine rockglaciers with annual surface velocity survey

N°	Name	Coordinates	Elevation m a.s.l.	Area km ²	Aspect	Available data	Mean horizontal velocity (2003/04) ma ⁻¹	Relative drop (2004-2006) %
1	Laurichard	45°01'N, 06°24'E	2424-2644	0.08	N	1999-...	1.03	-40
2	Mille	46°01'N, 07°12'E	2340-2430	0.02	NE	2003-...	0.05	-61
3	Aget-Rogneux	46°01'N, 07°14'E	2810-2890	0.03	SE	2001-...	0.20	-50
4	Mont-Gelé B	46°06'N, 07°17'E	2600-2740	0.02	NE	2000-...	1.20	-81
5	Mont-Gelé C	46°06'N, 07°17'E	2620-2820	0.05	N	2000-...	0.22	-42
6	Tsarmine	46°03'N, 07°30'E	2480-2650	0.04	W	2004-...	-	-
7	Beccs-de-Bosson/Réchy	46°10'N, 07°31'E	2610-2850	0.10	NW	2001-...	0.97	-36
8	Furggentälti/Gemmi	46°24'N, 07°38'E	2450-2650	0.03	N	1994-...	3.08	-52
9	HuHH1	46°11'N, 07°43'E	2630-2780	0.04	NNW	2001-2005	1.26	-
10	HuHH3	46°11'N, 07°43'E	2515-2650	0.05	NW	2002-...	1.78	-52
11	Büz North (Trais Fluors)	46°32'N, 09°49'E	2775-2840	0.02	NE	1998-2005	0.74	-
12	Ölgrube	46°54'N, 10°45'E	2380-2810	0.21	W	2000-2005	1.50	-
13	Reichenkar	47°03'N, 11°02'E	2310-2750	0.27	NE	1998-2006	3.15	-9
14	Weissenkar	46°57'N, 12°45'E	2610-2720	0.15	W	1999-...	0.08	-41
15	Hinteres Langtalkar (upper part)	46°59'N, 12°46'E	2455-2700	0.15	NW	1999-...		
	(lower part)		>2655	0.06			0.18	-28
			<2655	0.09			2.22	-21
16	Dösen	46°59'N, 13°17'E	2340-2650	0.19	W	1995-...	0.26	-19

Region 4: eastern Swiss Alps (Upper Engadine)

The Büz North (Trais Fluors) pebbly rockglacier comprises two superimposed lobes, 70 and 90 m long respectively. At the beginning of the survey in 1998, no pronounced morphological expression of flow was noticed. However, the movement turned out to be in the order of 1 ma⁻¹ and more (Ikeda et al. 2003, 2008, Käab et al. 2007).

Region 5: western Austrian Alps

Ölgrube rockglacier consists of two lobes of varying activity. Maximum annual velocities (1.5 ma⁻¹) occur in the central lower part. Seasonal variations were observed with a velocity decrease of about 50% during winter 2003 (Krainer & Mostler 2006, Hausmann et al. 2007a).

Reichenkar is a 1400 m long, very active tongue-shaped rockglacier. Highest velocity (up to 3 ma⁻¹) occurred in 2003/04. No seasonal variation was noticed in 2002 and 2003 (Krainer & Mostler 2006, Hausmann et al. 2007a, b).

Region 6: central Austrian Alps

Weissenkar is a slowly moving tongue-shaped rockglacier consisting of an upper lobe overriding a lower one and characterized by well developed furrows and ridges at the entire lower half of the rockglacier. Weissenkar rockglacier moves on average 0.02 to 0.11 ma⁻¹ (Kaufmann et al. 2006).

Hinteres Langtalkar houses a highly active tongue-shaped rockglacier which advanced over a prominent terrain ridge into steeper terrain most likely in 1994 (Avian et al. 2005). Several transverse crevasses developed since (e.g. Roer et al. 2008). The current movement pattern differentiates a faster lower part and a substantially slower upper part.

Dösen is a tongue-shaped rockglacier. Displacement measurements started in 1995 – including photogrammetric work of the preceding period until 1954 – revealing mean velocity rates of 0.13 - 0.37 ma⁻¹ (Kaufmann et al. 2007).

MAAT and MAGST in 2000-2007

Air temperature

The 1987-2007 mean annual air temperature (MAAT) in the Alps was on average 1 to 2°C warmer than during the preceding decades. Since 2000, two extreme warm climatic events affected the Alpine region: the heat wave of summer 2003 and the 2006/07 warm swell, namely 15 months of quasi continuous large positive temperature anomaly between April 2006 and June 2007 (except August 2006). Figure 2 shows that the 2003 heat wave induced a rapid warming of MAAT towards values exceeding those of earlier and later years (except in the Austrian Alps) and that the 2006/07 event resulted in an exceptionally high MAAT, which exceeded everywhere the 2003 value by 0.5 to 1.5°C.

Ground surface temperature

There is no borehole on the 16 observed rockglaciers, except a shallow one (6 m) at Trais Fluors. Ground surface temperature is nevertheless monitored on several of them. Variations of the mean annual ground surface temperature (MAGST) are used as a proxy for the permafrost

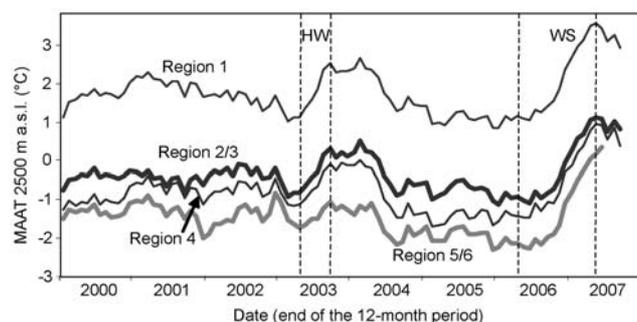


Figure 2. Mean annual air temperature (12-month running mean) standardized at 2500 m a.s.l. (gradient: -0.56°C/100 m). HW: heat wave 2003; WS: warm swell 2006/07. Region 1: St. Christophe, 1570 m a.s.l. (Météo-France). Region 2/3: Grand-St-Bernard, 2472 m a.s.l. (MeteoSwiss). Region 4: Säntis, 2490 m a.s.l. (MeteoSwiss). Region 5/6: Sonnblick, 3105 m a.s.l. (ZAMG – Central Institute for Meteorology and Geodynamics).

temperature changes at shallow depth even if the intensity of the winter cooling and summer warming (freezing and thawing index) should not be neglected. The snowcover buffering the ground-atmosphere heat exchanges for a long part of year, varying annual snowcover conditions alter the behavior of MAGST in comparison with MAAT: both are not evolving in a parallel way (Fig. 3). Despite the effect of snow, a homogeneous MAGST behavior is observed at the regional scale (e.g. Delaloye & Monbaron 2003). The larger variations of MAGST are also similar at the interregional scale in the Alps, with however some differences in 2005-2006 – colder values in the western regions 1-3 (Fig. 3). Three periods of warmer MAGST occurred in 2001, 2003/04 and 2007, with the 2003/04 event as the warmest.

Both 2003 and 2006/07 warm climatic events did not affect MAGST in the same way. In 2003, a strong MAGST increase already occurred during the winter due to earlier snow insulation (e.g. Vonder Mühl et al. 2007); a second phase of warming succeeded in summer and was caused by the heat wave. An extremely high MAGST value was reached by the end of 2003. In 2006/07, the situation was the reverse. Later and lesser snowfalls in early winter favoured the cooling of the ground surface in spite of the persistence of mild air temperature. The extremely high MAAT was strongly attenuated in MAGST.

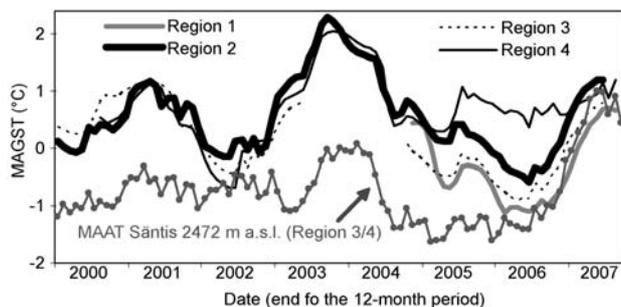


Figure 3. Interregional comparison of MAGST behavior in the western and central Alps (12-month running mean). Region 1 : Laurichard rockglacier (average of 2 sites of measurement). Region 2 : Beccs-de-Bosson/ Réchy (2). Region 3 : Furggentälti/ Gemmi (1). Region 4 : Trais Fluors (1).

Results

Despite variable size, morphology, complexity of flow field, mean annual velocity, seasonal rhythm, etc., the compared rockglaciers have shown a rather homogeneous and synchronous behavior (Fig. 4). Three phases of higher creep rate can be quoted in 2000/01, 2003/04 and 2006/07. They all followed immediately a period of warmer MAGST.

Every rockglacier reached an absolute or relative maximal creep rate in 2003/04 before a drastic drop occurred for most of them between 2004 and 2006 (up to -81%, Tab. 1). The drop was generally stronger to the west (regions 1-3) than to the east (regions 5-6). Stationary or slightly increased velocities were observed everywhere in 2006/07.

The situation in 2000/01 was more contrasted. A peak rate of deformation occurred in region 4 and was also almost reached in region 1. Relative maxima are reported from regions 3 and 6 (no data in region 2) whereas no maximum is documented in region 5. Neighboring regions did not display similar behavior in rockglacier movement.

Discussion

Neglecting small differences in interannual variations, that may be due either to internal and topographical characteristics of the rockglaciers, or to the variability of the seasonal rhythm, or to a shift in the measurement date, the rather homogeneous behavior of Alpine rockglaciers allows to state that: (1) the driving processes are likely to be the same for all observed rockglaciers; (2) there should be a common climatic control of the permafrost creep rate; (3) a dominant effect of active layer solifluction or surface boulder creep can be excluded, as corroborated for instance by borehole deformation measurements on the Trais Fluors rockglacier (Ikeda et al. 2008).

As the interannual changes of surface motion appear to be mostly correlated to the evolution of the MAGST with a delay of a few months (Fig. 4) - the warmer the MAGST, the larger the velocity -, one can infer that they should be caused by a thermally induced process. The delay being not long enough for the surface thermal signal to penetrate deeply into permafrost, interannual changes would thus be primarily caused by shifts in the deformation rate of shallow permafrost layers mostly located – if existing – above the shear horizon.

Higher creep rates should also be caused by the development of a thick winter snowcover, which, during early summer, provides more meltwater to penetrate into a warm rockglacier system. This process is evoked by Ikeda et al. (2008) to explain the high activity of the Trais Fluors rockglacier in 2001. In that region, the snowcover in winter 2000/01 was much deeper than for both the previous and the following winters. The unusually high amount of meltwater in early summer 2001 is advanced as a factor which facilitated permafrost creep. A similar situation occurred in the Laurichard area in the French Alps. The snow accumulation (2.42 m we) recorded that winter on the Sarennes glacier at a distance of 24 km was 0.65 m we above the 1984-2007 mean and the only value exceeding 2 m we since 1995 (Fig. 5). Among the six regions defined in this study, both Laurichard and Trais Fluors regions are the most exposed to southerly precipitations, a situation which prevailed in winter 2000/01.

Changing interannual creep rates may finally be related to the intensity of winter ground freezing. Where data is available, the maximal activity of rockglaciers appears to be linked to lower freezing index values. In the western and eastern Swiss Alps, the highest annual velocities occurred after the warmest winter on the ground surface, in 2001 and 2003 respectively (Fig. 6). On the Muragl rockglacier, close to Trais Fluors, seasonal velocity surveys carried out between 1998 and 2003 (Käab et al. 2007) showed that, contrary to other winters, the velocity of the rockglacier did not decrease during winter 2000/01. The higher annual velocity was caused by the absence of a winter deceleration.

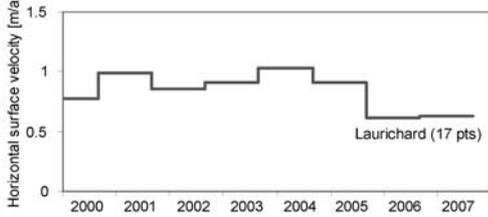
Conclusions and perspectives

Rapid and slow rockglaciers have shown mostly a similar kind of annual velocity variations in the whole arc of the European Alps since 2000. Interannual variations of rockglacier dynamics appear so far – with probably a few exceptions – to be primarily related to external climatic

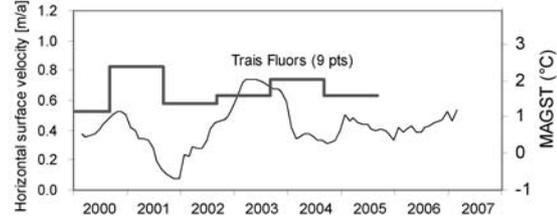
factors rather than to the internal characteristics of the rockglaciers. They are mostly well related to shifts in mean annual ground surface temperature with a few months of time lag reflecting the delay in propagation of corresponding anomalies deeper into permafrost. Seasonal

factors may play also an important role. A lower intensity of winter ground freezing and/or a larger amount of winter (October-May) snowfall facilitate a higher rate of annual rockglaciers surface motion.

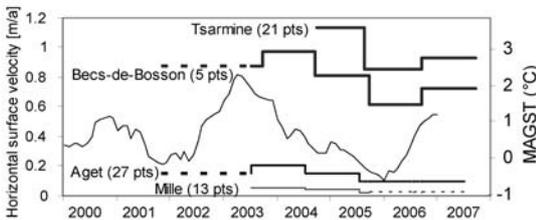
Region 1 : French Alps



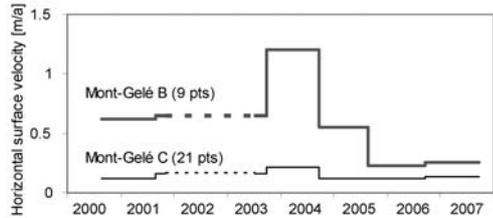
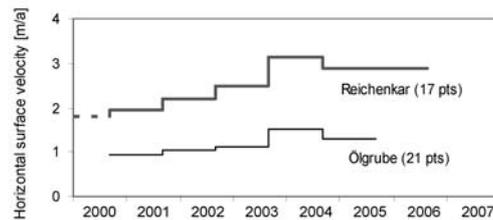
Region 4 : eastern Swiss Alps



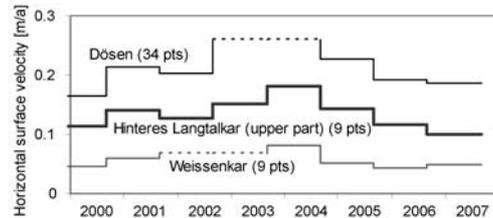
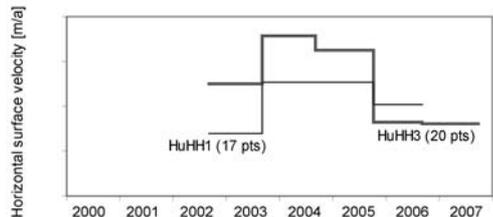
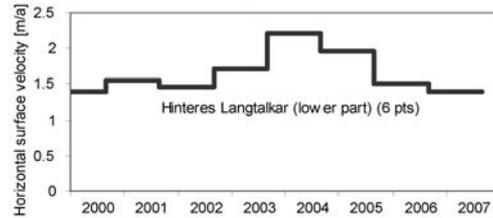
Region 2 : western Swiss Alps



Region 5 : western Austrian Alps



Region 6 : central Austrian Alps



Region 3 : north-western Swiss Alps

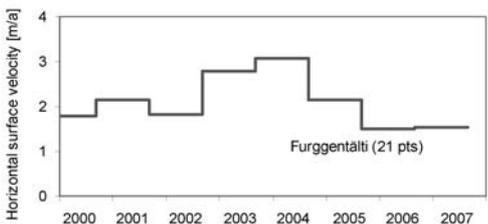


Figure 4. Annual horizontal velocities of alpine rockglaciers. The velocity scale is not identical on every graph. Dotted lines indicate a 2-year interval of measurement. Mean annual ground surface temperature (MAGST) at Becs-de-Bosson and Trais Fluors rockglaciers is inserted in the respective chart with date corresponding to the median of the 12-month period.

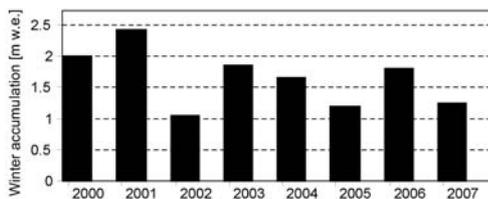


Figure 5. Winter snow precipitations (cumulative amount from October to April in metres of water equivalent, m we) recorded at Sarnes Glacier (French Alps).

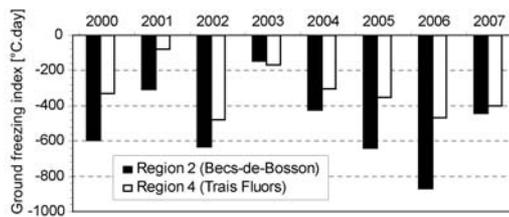


Figure 6. Interregional comparison of ground freezing index in the Swiss Alps.

The set of 16 rockglaciers that has been observed up to now is representative of six alpine regions. It establishes a pioneer network for the observation of short-term variations of rockglacier activity. The first synthetic results presented in this paper strongly encourage the continuation of the monitoring effort and the extension of the network to further regions, particularly in the southern Alps for which such data is still mostly lacking. The availability of uninterrupted series, complemented by ground surface temperature and snow data acquired on the rockglaciers or in their close vicinity, will serve a more precise identification and quantification of the factors driving the short-term behavior of permafrost creep rate in temperate mountain areas.

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