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Safety concept for hazards caused by ice avalanches from the Whymper hanging glacier in the Mont Blanc Massif

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ABSTRACT

The Whymper glacier is a hanging glacier located on the south face of the Grandes Jorasses (Mont Blanc Massif, Italy). Combined snow and ice avalanches triggered by ice masses breaking off from the hanging glacier endanger the village of Planpincieux and its surroundings in the Val Ferret. In 1997, the SLF and the VAW developed the first safety concept for the village for several scenarios based on the monitoring of the glacier and an assessment of the local avalanche hazard. At the end of June 1998 almost the entire Whymper glacier (around 150,000 m^3) sheared off and the ice avalanche stopped only 500 m above the valley road. The Whymper glacier has grown back and now has a similar surface topography as in 1998. The SLF and VAW improved the 1997 safety concept by considering several scenarios of falling ice volumes. The different ice avalanche scenarios were simulated using the 2-dimensional calculation model RAMMS. The necessary safety measures are defined in relation to the local avalanche danger level and the potential volume of an icefall. The hanging glacier is continuously monitored with a system consisting of a total station, GPS-stations, seismic sensors and visual observations. The improved safety concept has been operational since 2009. However, a dangerous icefall has not occurred yet.

1. Introduction

The Whymper hanging glacier is an unbalanced cold ramp glacier located on the south face of the Grandes Jorasses (Mont Blanc Massif, Italy; Figs. 1 and 2) at an elevation of 4000 m a.s.l. (Pralong and Funk, 2006). Snow avalanches and combined snow-ice avalanches triggered by ice masses breaking off from the hanging glacier can endanger the village of Planpincieux and its surroundings in the Val Ferret (Fig. 3). The valley is heavily frequented by tourists both in winter and summer. For the local authorities responsible for safety in the Val Ferret, the key problem is to organise the necessary safety measures by taking into account both the local avalanche danger and the risk of an impending icefall. In 1997 the SLF and the VAW worked out a first safety concept for different scenarios based on different volumes of icefalls and the local avalanche hazard (Margreth and Funk, 1999). If an ice avalanche with a volume of 30,000 m^3 is released in winter in combination with a stable snowpack we recommended to close the road into the Val Ferret. However if the snowpack stability is considered to be poor we proposed that the village of Planpincieux be evacuated.

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In the night between 31 May and 1 June 1998 almost the entire Whymper glacier (around 150,000 m^3) sheared off. The avalanche stopped 500 m above the road into the Val Ferret (Fig. 3). The horizontal and vertical distances were 3000 m and 2200 m respectively. After this event, the ice avalanche activity was strongly reduced. However, the hanging glacier progressively reformed and in 2009 both the volume and the geometry of the Whymper glacier were similar as in 1997 (Fig. 2). In the autumn of 2008, a crevasse opened in the lower part of the hanging glacier and a new instability was suspected by the local authorities. Consequently, SLF and VAW were mandated to revise the 1997 safety concept (Margreth, 2009).

2. Glaciological, topographical and avalanche situation

The current ice volume of the Whymper glacier is estimated to be 150,000–200,000 m^3. The front of the glacier is about 90 m wide and its surface area is about 25,000 m^2. The normal ablation zone of the hanging glacier is the glacier front where ice lamellas with typical volumes of less than 30,000 m^3 break off periodically. The return period is estimated to be 1–2 years. According to observations, these smaller icefalls come to a stop above the valley floor if they occur in summer or in winter if the snowpack is stable. A secondary release of snow avalanches has not been documented. As the current geometry of the Whymper glacier is comparable to that in 1997, the whole ice mass could be detached again.

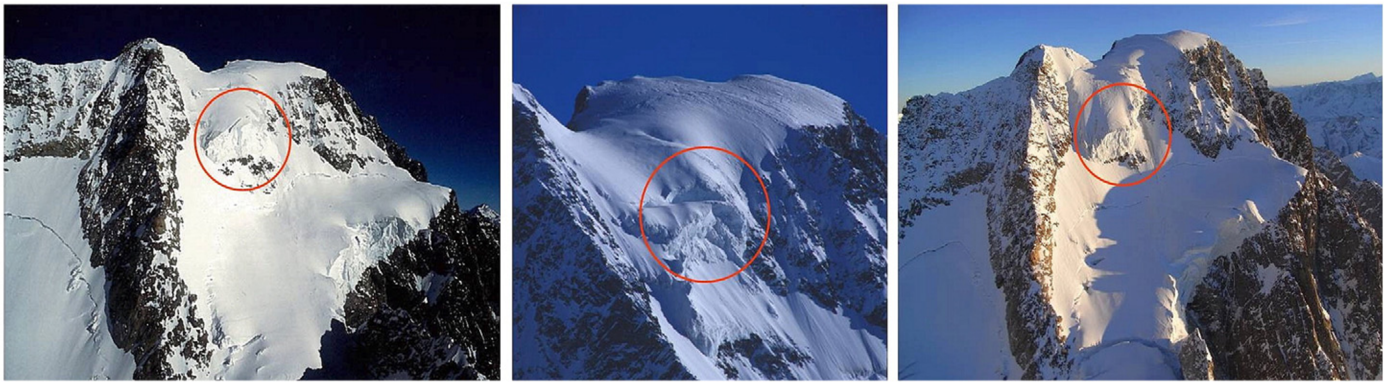

Fig. 1. Whymper glacier, Grandes Jorasses – January 1997 (left), after 1 June 1998 icefall (middle, Photo R. Cosson), January 2009 (right).

We estimate the return period of such an icefall to be at least 15–30 years. The surface area and the length of the glaciers along the expected track of an ice avalanche are now somewhat smaller than in 1997. However, the main features relevant for the avalanche flow such as the extent of the strongly crevassed zones or the glacier geometry immediately below the hanging glacier are comparable. The four main avalanche tracks that we distinguished in 1997 are still valid (Fig. 3). The extent of possible starting zones for snow avalanches is very large, with an area of about 180 ha. The potential avalanche volume is in excess of 1.0×10^6 m^3. The formation of powder avalanches is likely because of the steep avalanche tracks with mean slope inclinations of 28°–33°, an elevation difference of up to 2400 m and rocky outcrops along the track. For the hazard assessment and the elaboration of the safety concept we investigated three different classes of ice volumes breaking off from Whymper glacier:

- Small ice volume $<$10,000 m^3 (unforeseeable event)
- Medium ice volume of ca. 30,000 m^3 (ice lamellas on the glacier front)
- Maximum ice volume of ca. 150,000 m^3 (slab fracture of the whole Whymper glacier)

3. Avalanche dynamics calculations

3.1. Fundamentals

The goal of the avalanche dynamics calculations is to quantify the runout distances of different avalanche scenarios in relation to the three volume classes of icefalls and varying snow conditions. The main difficulty is to assess the consequences of the impact of an icefall on the snowpack. The largest known combined snow/ice avalanche events are typically observed in winter (such as the events at Weisshorn east face glacier, Randa, Switzerland or Gutzgletscher, Bernese Alps, Switzerland; Raymond et al., 2003). Well documented cases are very rare. If a small- or medium-sized ice volume impacts a stable snowpack, snow can be entrained. However, according to our observations, the release of a secondary snow avalanche is unlikely. The approximately 25,000 m^3 icefall of the Whymper glacier in January 1997 did not release a snow avalanche. If the impact is caused by a large ice volume ($>$100,000 m^3) or if the snowpack is unstable, the release of a secondary snow avalanche is more likely.

Fig. 2. Whymper glacier, January 2009 (total volume ca. 150,000–200,000 m^3).

Interesting observations where rock avalanches impacted snow covered slopes or snow covered glaciers have been reported. On January 18 1997, the impact of a falling rock volume of 2×10^6 m^3 on the Brenva glacier mobilized more than 4.5×10^6 m^3 of ice and snow along the track (Deline, 2009). The horizontal and vertical distances were 5500 m and 2150 m respectively. On 24 December 2008, the Crammont rock avalanche, 10 km east of Mont Blanc, reached a horizontal and vertical distance of 3400 m and 1560 m respectively, with an initial rock volume of 0.4×10^6 m^3 (Deline et al., 2010). Such long runout distances of mixed avalanche events occur because entrained ice and snow reduce the friction and fluidize the moving mass. In the Whymper glacier case, we assume that an icefall with a maximum volume of 150,000 m^3 will release or entrain most of the snowpack along the avalanche path. However, we do not expect erosion of the glaciers along the avalanche track. As the potential snow avalanche volume below the Grandes Jorasses is much larger than the largest expected falling ice volume, the runout distances of such combined snow/ice-avalanches will be similar to what was observed in the case of snow avalanche events. We expect that the friction of a pure snow avalanche is smaller than that of a mixed snow/ice-avalanche. A mixed snow/ice avalanche is expected to behave similar to wet snow avalanches because of heavy impacts of ice clods and the high flow density.

3.2. Models applied

The ice avalanches were simulated with the 2-dimensional avalanche calculation model RAMMS (SLF, 2010). RAMMS was specially designed as a practical tool for the calculation of snow avalanches, debris flows and rock fall. RAMMS numerically solves a system of partial differential equations, governing the depth-averaged balance laws for mass, momentum and random kinetic energy using first and second order finite volume techniques. The model is based on a Voellmy-fluid friction model. The computational grid was generated from a Digital Elevation Model with a 10 m resolution. The hazard assessment in 1997 was based on the results of 1-dimensional avalanche calculations with the model AVAL-1D (SLF, 2005) where the primary flow directions, the flow width and the mass distributions had to be determined in advance.

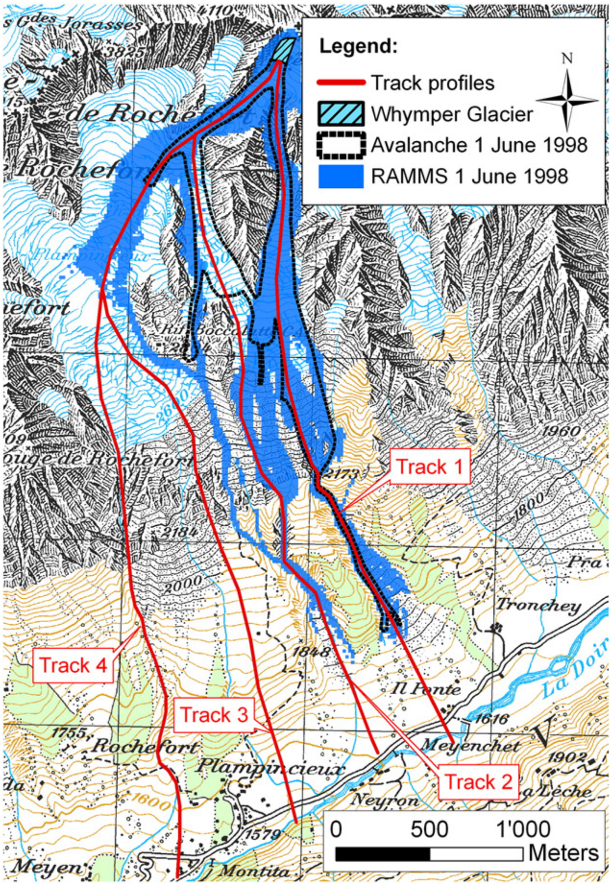

Fig. 3. Observed extent 1 June 1998 ice avalanche with possible tracks and RAMMS simulation of the 1 June 1998 ice avalanche.

This is problematic in the case of a highly complex topography such as the avalanche flow path below the Grandes Jorasses. RAMMS is more appropriate for such rough terrain conditions resulting in a more reliable distribution of the avalanche mass along the different tracks. RAMMS has been extensively applied in Switzerland in the past years for the calculation of snow avalanches (Christen et al., 2010a). Recently, RAMMS has also been successfully used for the physically based modeling of rock and rock-ice avalanches (Allen et al., 2009 and Schneider et al., 2010). The model was considered to be a useful tool for analyzing flow patterns and calculating flow velocities. However, the model has so far only been applied a few times for the calculation of velocities and runout distances of ice avalanches and is not yet well calibrated for this purpose. Caution is therefore required in the interpretation of the obtained runout zones and other parameters such as velocities or flow depths.

3.3. Input parameters

The main input parameters for the calculation of ice avalanches with RAMMS are the following:

Release volume: The three ice volumes described in the section above were considered. The geometry of the falling ice masses was specified as realistically as possible. The fracture depths of the ice avalanches were varied between 4.9 m and 21.0 m. It was assumed that the glacier ice disaggregates during the fall and that the density of the ice decreases from an estimated 850 to 900 kg/m^3 to about 400 to 500 kg/m^3. The initial ice volume was increased by a factor varying between 1.5 and 2.0 to compensate for the decrease in density which RAMMS does not consider and the poorly known mass distribution in the model calculation (Table 1).

Snow entrainment: The largest uncertainty in the avalanche dynamics calculations is associated with the treatment of the impact of a falling ice mass on a snowpack. We approached this problem with the RAMMS entrainment module where an erodible snow cover can be specified (Christen et al., 2010a). This requires the definition of the snow cover density, the erodible snow depth, the entrainment parameter K and the area where snow can be entrained. In field studies of snow avalanches, the entrained mass was found to depend mainly on the avalanche velocity and the available snow mass (Sovilla et al., 2007). A velocity driven erosion law is implemented in RAMMS such that an entrainment parameter K defines the volumetric entrainment rate per unit avalanche velocity (Christen et al., 2010b). If the snowpack is unstable an ice avalanche will entrain a 1.5 m thick snow layer by frontal plugging and the secondary release of snow avalanches is likely (Table 2). For such situations an entrainment parameter K of 1 was chosen. The snow cover with an estimated density of 200 kg/m^3 is entrained instantaneously. For a stable snowpack we applied a smaller entrainment parameter ($K = 0.2$) and a smaller erodible snow depth. Compared to an unstable snowpack ($K = 1$) the snow is entrained at a much lower rate. Furthermore, the size of the surface areas with potential snow entrainment was varied as a function of the snowpack stability (Fig. 4). To quantify the snowpack stability and the release probability of snow avalanches, the five danger levels of the European Avalanche Danger scale (SLF, 2008) were used.

Friction parameters: The Voellmy-fluid friction model divides the frictional resistance into the dry-Coulomb type friction (frictional parameter μ) that scales with the normal stress and the velocity-dependent turbulent friction (frictional parameter ξ). The two parameters were calibrated for snow avalanches as a function of the avalanche volume, terrain features, the elevation and the return period (Table 2). Ice as well as combined snow-ice avalanches were simulated with the same friction values as for snow avalanches (SLF, 2010). For small ice volumes and a stable snowpack, the friction parameter values corresponding to small volumes and a 10 year return period were used (for unchannelled topography $\mu = 0.26$ and $\xi = 2000$ m/s^2). For extreme situations when the ice avalanche releases large snow masses, the most extreme friction parameters for large volumes and a 300 year return period (for unchannelled topography $\mu = 0.155$ and $\xi = 3000$ m/s^2) were used. In general, large avalanches exhibit smaller friction parameters than small avalanches.

3.4. Results

First we tested the performance of RAMMS by back-calculation of the June 1998 ice avalanche. The initial release volume was set at 260,000 m^3 which is 1.7 higher than the estimated ice volume of 150,000 m^3. The ice avalanche did not entrain significant amounts of snow. We therefore neglected snow entrainment in the back-

Table 1
Overview of the release and entrainment volumes for the investigated ice fall scenarios at the Whymper Glacier.

Icefall scenario	Ice volume	Release volume considered in RAMMS simulations	Entrainment volume for danger level 1 “Low”	Entrainment volume for danger level 4/5 “High/Very high”
Small	10,000 m^3	20,000 m^3	10,000 m^3	830,000 m^3
Medium	30,000 m^3	50,000 m^3	70,000 m^3	930,000 m^3
Large	150,000 m^3	260,000 m^3	270,000 m^3	1,020,000 m^3

Table 2
Entrainment parameters in relation to the snowpack stability (K = 0: no snow entrainment; K = 1: the whole snowpack will be entrained) and applied friction values. The friction parameter categories of RAMMS depend on the avalanche volume (small: <25,000 m^3, medium: 25,000–60,000 m^3 and large: >60,000 m^3), the elevation (below 1000 m, 1000–1500 m and above 1500 m), terrain features (open slope, flat terrain, channel, gully and forested /unforested) and the return period (10, 30, 100 and 300 years). Examples of the μ/ξ friction parameters are given in the table for the terrain feature category "open slope" and for an elevation "above 1500 m".

Snowpack stability	Entrainment, snow density 200 kg/m^3		μ/ξ Friction value category			Danger level
	Snow depth (m)	Parameter K	Ice volume 10,000 m^3	Ice volume 30,000 m^3	Ice volume 150,000 m^3	
High	0.4–0.5	0.2	Small,10 y. $\mu = 0.26$ [−] $\xi = 2000$ [m/s^2]	Medium,10 y. $\mu = 0.225$ [−] $\xi = 2500$ [m/s^2]	Large 30 y. $\mu = 0.17$ [−] $\xi = 3000$ [m/s^2]	1 "Low"
Moderate	0.4–0.6	0.4–1	Medium,10 y. $\mu = 0.225$ [−] $\xi = 2500$ [m/s^2]	Large 10 y. $\mu = 0.18$ [−] $\xi = 3000$ [m/s^2]	Large 30 y. $\mu = 0.17$ [−] $\xi = 3000$ [m/s^2]	2 "Moderate"
Moderate-Weak	0.6	1	Medium,10 y. $\mu = 0.225$ [−] $\xi = 2500$ [m/s^2]	Large 10 y $\mu = 0.18$ [−] $\xi = 3000$ [m/s^2]	Large 30 y. $\mu = 0.17$ [−] $\xi = 3000$ [m/s^2]	3 "Considerable"
Weak	1.5	1	Large, 30 y. $\mu = 0.17$ [−] $\xi = 3000$ [m/s^2]	Large 100 y. $\mu = 0.16$ [−] $\xi = 3000$ [m/s^2]	Large 300 y. $\mu = 0.155$ [−] $\xi = 3000$ [m/s^2]	4/5 "High"/"Very high"

calculation. The frictional parameters that led to the best simulation of the runout distance were $\mu = 0.35$ and $\xi = 1350$ m/s^2. These friction values differ significantly from the most extreme friction parameters obtained so far because the ice avalanche did not entrain much snow and because the lower part of the avalanche track was free of snow. The RAMMS simulation reproduced the extent along the main avalanche axis relatively well. However, there was too much lateral spreading on the Planpincieux glacier and in the lower part of the avalanche path. This could be due to differences between the Digital Elevation Model from 2005 and the topography of 1998 (Fig. 2).

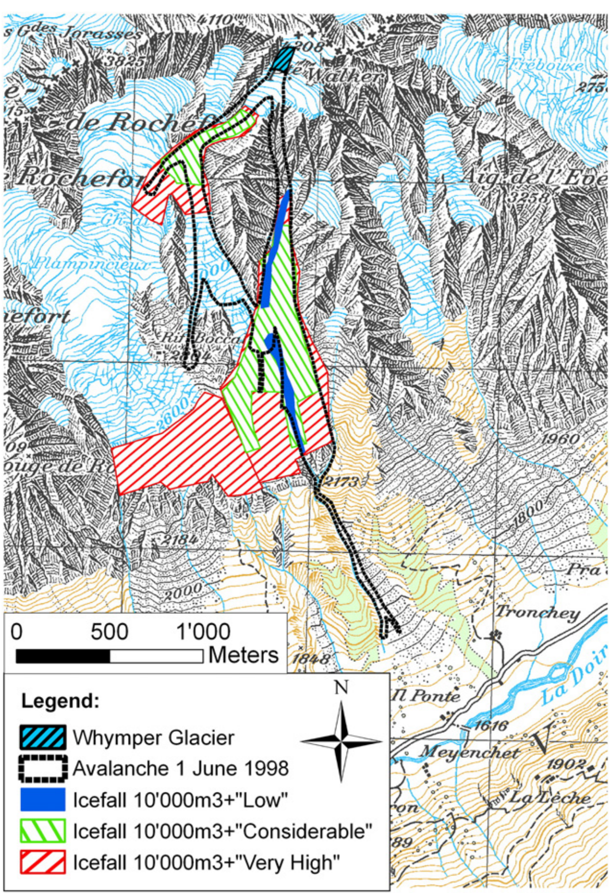

Fig. 4. Whymper glacier, extent of 1 June 1998 ice avalanche and potential snow entrainment areas for an icefall volume of 10,000 m^3 and three different danger levels.

We calculated 14 different scenarios with RAMMS for the hazard assessment (Fig. 5). According to these calculations, the danger level "Considerable" is the threshold at which the valley bottom can be endangered by an icefall with a volume of 10,000 m^3. The entrainment volumes vary from 10,000 m^3 for a stable snowpack (Danger level "Low") to over 900,000 m^3 for an extreme avalanche situation with an unstable snowpack. If an icefall of 30,000 m^3 occurs during a time period with a stable snowpack (danger level "Low") the dense part of the avalanche does not reach the valley road, but the air pressure of the powder part cannot be neglected. If the snowpack is only moderately to weakly bonded (danger level "Moderate"/"Considerable"), around 250,000 m^3 of snow will be entrained and the avalanche reaches the valley bottom along tracks 1 and 2. Ice avalanches with an initial ice volume of 150,000 m^3 always reach the valley bottom regardless of the danger level. If the danger level is "High" or "Very High" the village of Planpincieux can be endangered. The hazard area is similar to the extent of extreme snow avalanches. If an icefall occurs during a period with a danger level "High" or "Very High", the consequences are also very serious for small initial ice volumes. The icefall is only the trigger for the snow avalanche irrespective of the initial ice volume since the released snow masses are much larger than the ice masses.

4. Safety concept

The safety concept recommends temporary security measures depending on the local avalanche danger level in combination with the volume of an impending icefall from the Whymper glacier (Table 3). The zones that have to be closed or evacuated for a certain scenario are delineated on a map that forms a part of the safety concept (Fig. 6). If for example an icefall with a volume of 20,000 m^3 is expected and the local avalanche danger level in the Val Ferret is "Considerable" we recommend that the zones A and B be closed. The safety concept was improved compared to the situation in 1997, ice volumes smaller than 10,000 m^3 were also included and the safety plan was refined. An important input factor is the local avalanche danger level in the Val Ferret. The danger level depends on the snowpack stability, the triggering probability by an ice avalanche, the number and extent of dangerous slopes and the potential avalanche volume. An important point is that the impact of an icefall on the snowpack can generate a very large surcharge, which is much higher than the classical additional load (e.g. a group of skiers or an explosion) considered in the definition of European avalanche danger scale (SLF, 2008). We recommend therefore to stay a few days longer on the danger level 4 ("High") or 5 ("Very High") than customary and to evaluate the danger level very carefully if a weak layer is covered by thick snow layers. Three different ice volume categories are defined in the safety concept. The potential volume of an

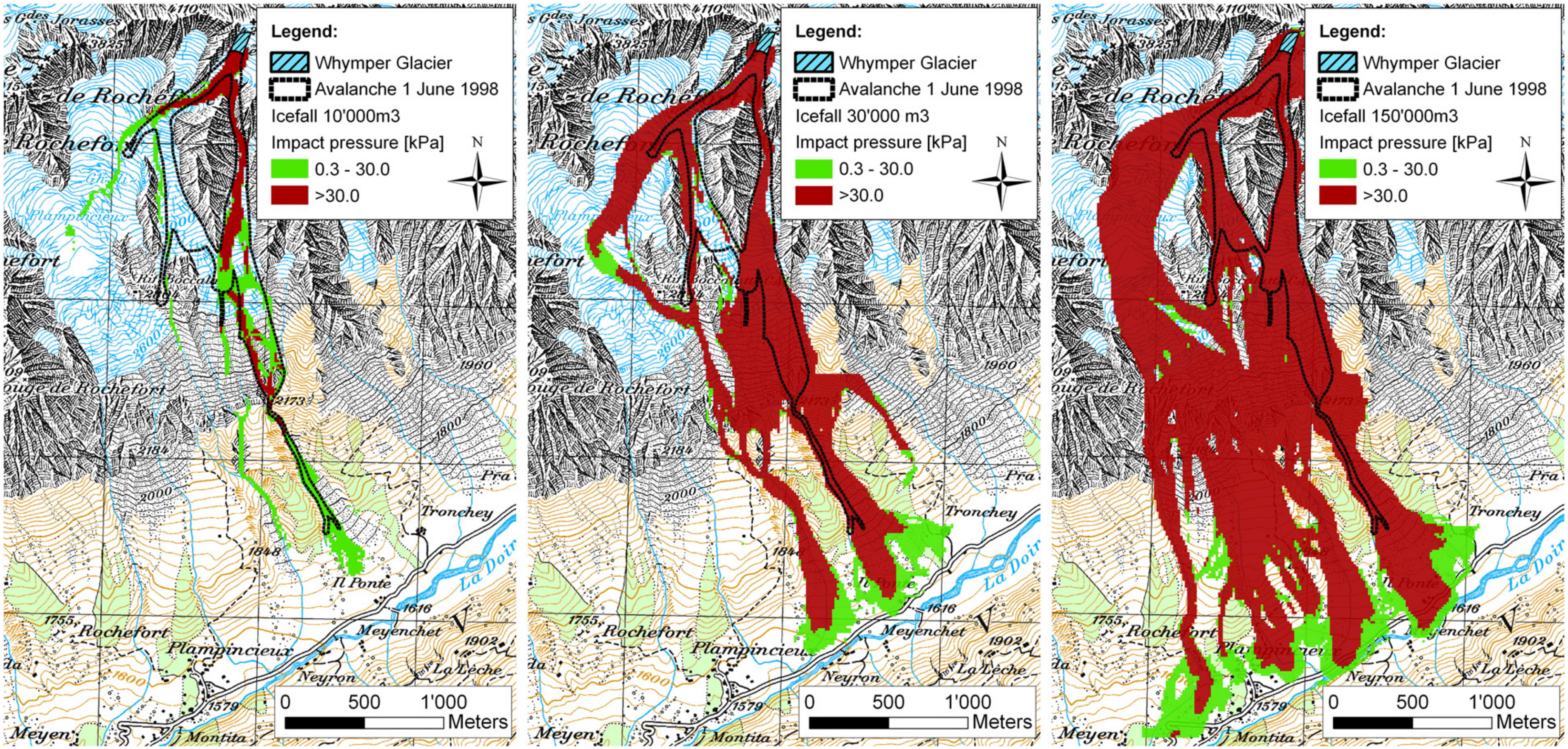

Fig. 5. Results of avalanche dynamics calculations using RAMMS for small, medium and maximum ice volumes (left: icefall 10,000 m^3 with danger level “Low”; middle: icefall 30,000 m^3 with danger level “Considerable”; right: icefall 150,000 m^3 with danger level “High”).

Table 3
Safety concept for Planpincieux, Val Ferret, regarding temporary measures during winter. The necessary security measures are determined as a function of the prevailing ice volume which can break loose at the Whymper glacier and the actual local avalanche danger level in the Val Ferret.

Local avalanche danger level Val Ferret:	Ice avalanche volume Whymper glacier:		
	<10,000 m^3	10,000 m^3–30,000 m^3	30,000 m^3–150,000 m^3
1 Low	No safety measures	Evacuation of zones A and B	Evacuation of zones A, B and C, Curfew zone D
2 Moderate	No safety measures	Evacuation of zones A and B	Evacuation of zones A, B, C and D
3 Considerable	Evacuation of zones A and evtl. B	Evacuation of zones A and B	Evacuation of zones A, B, C and D
4 High	Evacuation of zones A, B and C	Evacuation of zones A, B and C, Curfew zone D	Evacuation of zones A, B, C and D
5 Very high	Evacuation of zones A, B, C and D	Evacuation of zones A, B, C, D	Evacuation of zones A, B, C and D

icefall at a specific date has to be assessed with the monitoring system described in the following section. In the past, the break-off of unstable ice masses could be successfully forecasted on several occasions (Pralong et al., 2005, Röthlisberger, 1981 and Wegmann et al., 2002).

5. Monitoring system

5.1. Overview

The Whymper glacier has been regularly monitored using visual observations, aerial photographs and topographic measurements. According to the observations in autumn 2008, the opening of a new crevasse could be detected, which led to the investigations presented in this paper. A new monitoring system was installed in 2009 consisting of stakes with prisms on the glacier surface (Fig. 7) and an automatic total station (theodolite and a distometer) located in the valley (Vagliasindi et al., 2010) at a distance of ~4.7 km from the glacier. Surface displacements measurements are monitored at one-hourly intervals to detect an acceleration of an unstable ice mass. The measurements require good visibility and the stakes need to be reinstalled from time to time. New technologies were therefore applied and are still being tested to improve the reliability of the monitoring system. Close range photogrammetry techniques were used to quantify volume change of the hanging glacier and the widening of crevasses (Figs. 7 and 8). A low cost GPS station was installed to obtain surface displacement data independently of the prevailing weather conditions. A network of GPS stations was installed in the fall of 2010. In addition a seismic observation system consisting of a Taurus seismograph (Nanometrics, Inc.) with a single geophone (Lennartz 3D-LITE, 1 Hz) was installed at an elevation of 4100 m to measure the seismic activity of the glacier. Changes of seismic activity can indicate the imminent rupture of a hanging glacier. Combined motion-seismic monitoring systems are a promising way to improve the prediction of the break-off of a hanging glacier (Faillettaz et al., 2008). Finally, a ground based SAR-system (Synthetic Aperture Radar) was tested to estimate the volume of the unstable ice masses and a GPR (Ground Penetrating Radar) helicopter survey was used to determine the ice volumes.

5.2. Results from 2010 survey

Surface displacements were measured continuously during 2010. Fig. 7 indicates the position of the different monitored points. In addition, two reference reflectors were installed on the rock beside the glacier for the correction of the measurements for variable meteorological conditions. Using the same correction techniques as described in Faillettaz et al. (2008), an accuracy of around 1 cm for the distance measurements was obtained. The surface velocities of the different monitoring points could be determined from these measurements (see Fig. 9). The average surface velocities were around 4 cm to 5 cm per day until the beginning of June 2010 and no acceleration was observed. The total displacement of the reflector "prisma6b" was around 8 m between mid-January and 7th July 2010 (see Fig. 11). Some interesting results can be pointed out from the measurements of the surface velocities:

- The reflector "prisma2" located above the middle crevasse (see Fig. 7) moved with a lower velocity than the reflectors located below the crevasse ("prisma7b", "prisma8b", "prisma9b" and "prisma10b").
- The measured velocities increased during summer, probably due to the higher water content in the firn/ice at depth.
- The motion of the reflectors "prisma3b" and "prisma6b" (see Fig. 7) situated on the lamella at the front of the Whymper glacier started to accelerate in June 2010. This acceleration of the two reflectors

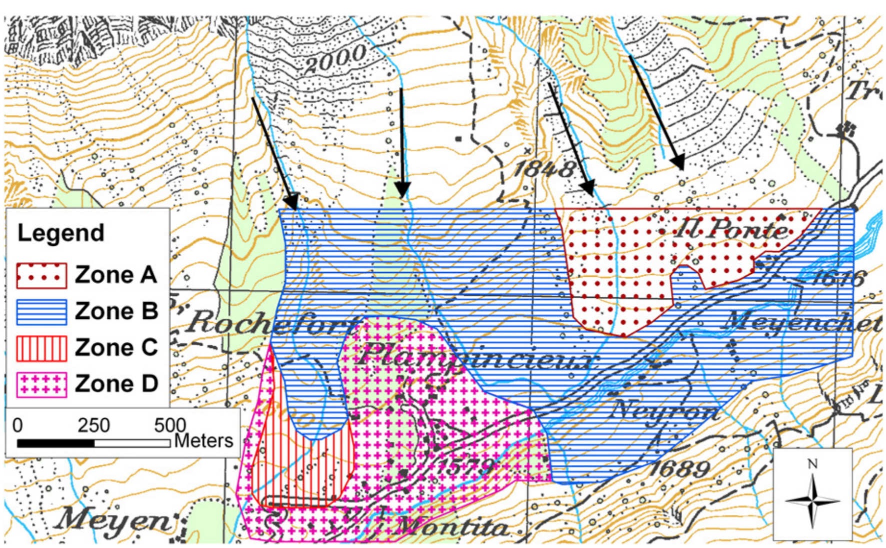

Fig. 6. Safety plan for Planpincieux, Val Ferret, regarding ice and snow avalanches from the Whymper glacier. The zones A, B, C and D refer to Table 2 and denote the area to be closed as a function of the prevailing ice volume and the local avalanche danger level.

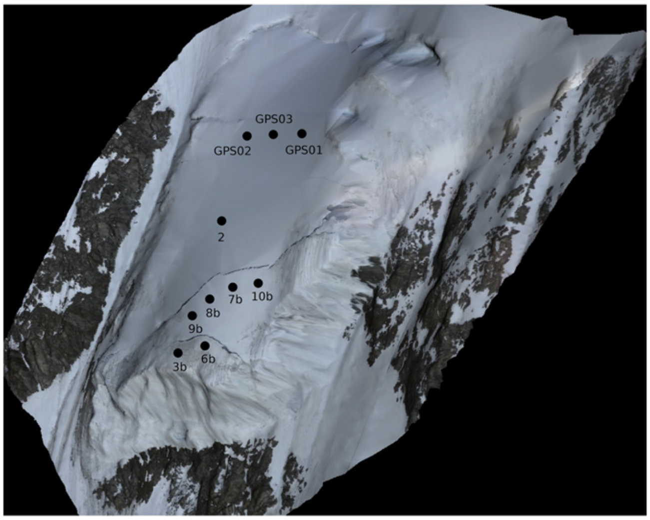

Fig. 7. Photogrammetric analysis of the Whymper glacier performed on the 8th July 2010. The positions of the 7 reflectors and the 3 GPS stations are also shown. The ice lamella with the reflectors "prisma3b" and "prisma6b" broke off on 24th July 2010.

prompted us to alert the authorities of an impending icefall, which then occurred on the 24th of July 2010. This event is analysed in Section 5.3.

- In mid July 2010, the velocity of reflector "prisma2" decreased, whereas the velocities of the other reflectors situated below the middle crevasse increased. This phenomenon is associated with the opening of the middle crevasse (Fig. 8) indicating a decoupling between upper and lower part of the Whymper glacier.
- After the opening of the middle crevasse, the surface velocities decreased to 5 cm per day, indicating a restabilization of the Whymper glacier. The reason for this restabilization remains unclear (the width of the middle crevasse crossing the whole glacier is still increasing).

During this period, a close-range photogrammetric analysis of the Whymper glacier was performed. By comparing two Digital Elevation Models acquired with one year separation in time, a slight thickening of the glacier behind the front and a thinning in the upper part could be seen. This observation indicates an ice mass transfer from the top to the front of the glacier (Fig. 10) which may indicate a progressive

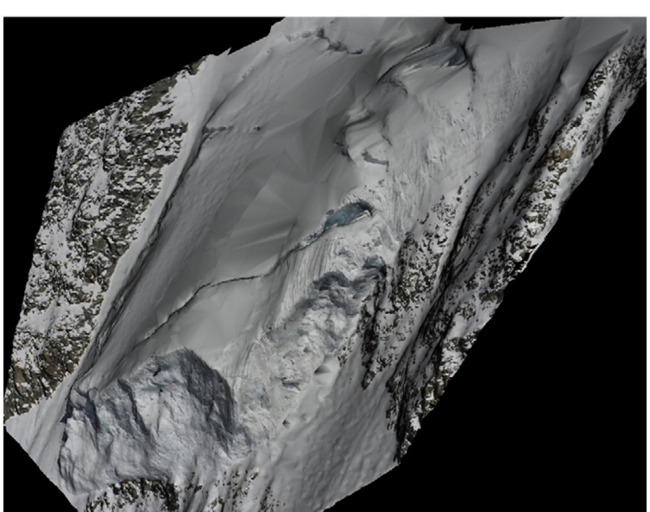

Fig. 8. Photogrammetric analysis of the Whymper glacier performed on the 31st July 2010. The opening of the medium crevasse as well as the small icefall from 24th July 2010 at the glacier front can be seen.

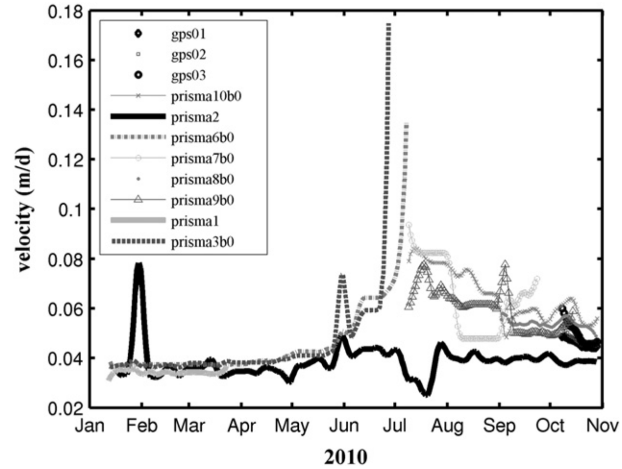

Fig. 9. Velocities of the Whymper glacier measured during 2010 at the different reflectors and GPS stations plotted on Fig. 6.

development of microcracks in an ice layer located just above the bedrock in the middle part of the glacier. This process could lead to a global destabilization of the glacier in the coming months/years similar to the event in June 1998 when an ice volume of around 150,000 m^3 sheared off. If such an event were to occur in winter, the safety concept (Table 3) recommends very extensive safety measures.

5.3. Icefall event on the 24th of July 2010

As mentioned in the previous section, a simultaneous acceleration of the two reflectors ("prisma3b" and "prisma6b") was detected at the end of June 2010 (see Fig. 7). Unfortunately the measurements stopped on the 27th of June 2010 for the reflector "prisma3b" and on the 7th of July 2010 for reflector "prisma6b", because the stakes toppled over due to surface melting. Following Faillettaz et al. (2008), we fitted the displacement measurements with a log-periodic power law acceleration model. It has been demonstrated that such a function is suitable to predict the failure time of an unstable ice mass. According to the results obtained with the measurements on "prisma6b" (Fig. 11) the surface velocity was expected to increase to 30 cm per day by July 24th, which was the day when the icefall occurred. Note that the displacement measurements stopped 15 days prior to the rupture. Surface measurements at reflector "prisma3b" could not be used for predictions because of stake stability problems.

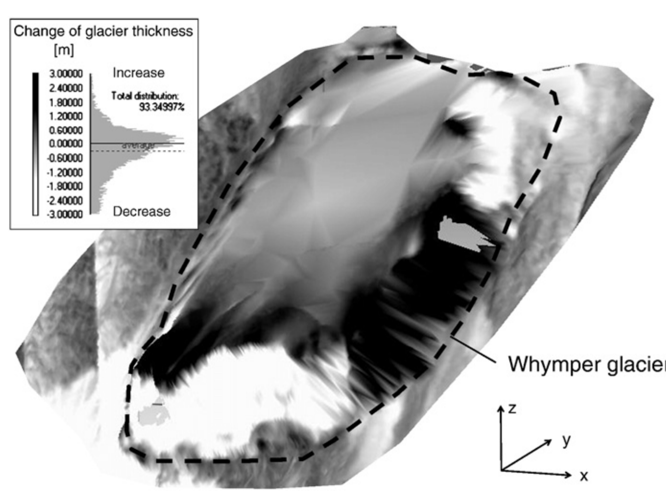

Fig. 10. Change of glacier thickness of Whymper glacier based on a comparison between two Digital Elevation Models performed between June 2009 and June 2010. Black colour indicates where the glacier thickness increased and white colour where it decreased.

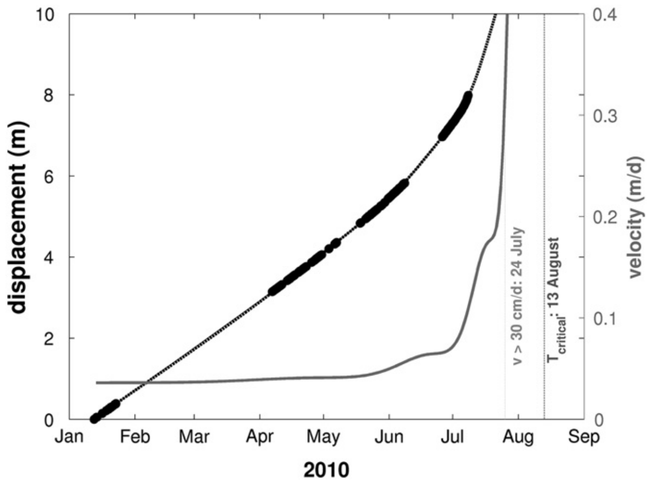

Fig. 11. Measurements of surface displacements at the reflector "prisma6b". These measurements stopped on the 7th of July 2010. The log-periodic power-law fit of the displacements is shown with the black dotted curve and the velocity with the grey line. The singularity (i.e. infinite velocity) was found to occur on 13th of August 2010, whereas a critical velocity of 30 cm/day was expected for 24th of July 2010. A velocity of 30 cm per day is classified as critical on the basis of past experience.

The volume of the icefall was estimated to be 7000 m^3 based on the photogrammetric measurements. This avalanche was not large enough to reach the valley bottom. According to the safety concept (Table 3), no safety measures were proposed for such situations.

6. Conclusions and outlook

The safety concept described here has been in effect since 2009. During the winter 2009/2010 the hanging glacier moved downwards with a rate of approximately 4 to 5 cm per day and no acceleration was observed. After an intense snow fall period followed by a temperature rise the avalanche danger level was "High" and the valley was closed to the public for one week. Two small icefalls with an estimated total volume of less than 10,000 m^3 occurred in the beginning of April 2010. An icefall occurred from a hanging glacier below the Whymper glacier on 10 June 2010. The runout was comparable to the icefall of 1 June 1998 but the ice volume was probably much smaller. Another icefall with a volume of 7000 m^3 took place on 24th July 2010. This icefall could be accurately forecasted thanks to the monitoring system and the authorities were warned in time.

The uncertainties in the analysis of snow/ice-avalanche processes are rather large. In particular, the interaction of ice avalanches with the snowpack and the dynamics of such combined ice/snow avalanches are still poorly understood. Careful monitoring and analysis of future icefalls in winter at the Whymper glacier and other locations will contribute to an improved understanding of this phenomenon.

The safety concept can only be applied if the volume of the impending icefall can be estimated. Combined motion-seismic monitoring systems seem to be a promising way to improve the forecast of the break-off of a hanging glacier. Further improvements in the assessment of the avalanche hazard and the evolution of the dynamics of hanging glaciers in a changing climate are nevertheless still necessary.

The application of the avalanche calculation model RAMMS delivered very promising results. However, at present the model is not well calibrated for the calculation of ice avalanches. The calibration of RAMMS could be improved with more detailed modeling studies based on observed ice avalanches with different volumes and ground roughness.

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