SUPPORTING INFORMATION FOR "DYNAMICS OF GLIDE AVALANCHES AND SNOW GLIDING"

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1. GLIDE AVALANCHE ACCIDENT OF SAINT-FRANÇOIS-LONGCHAMP

1.1. Location and Meteorological Conditions

Saint-François-Longchamp is a ski resort located in the Grande Lauzière mountain range, which is on the western border of the Vanoise massif, one of the highest massifs in the French Alps. With a total precipitation close to 1600 mm at 1000 m, this mountain range receives a fair amount of snow every winter season: about 4.5 m at 1000 m and from 7 to 9 m at 2000 m. Fall 2011 was characterized by a dearth of snow, low precipitation, and mild temperatures even at high altitudes. The season began on 3 December with abundant snowfall, which occurred on warm ground and was accompanied by strong winds. Then several storms swept through the Alps, leaving more than 2 m of snow at 2000 m. With the freezing point rising above 2000 m after Christmas, heavy rain caused a number of glide avalanches at low and medium altitudes. Between Christmas and New Year, snowfall accumulation was above average in most regions in the Alps and hit record levels locally. There was some evidence that Saint-François-Longchamp had close to half its annual average snowfall in December, but as there was no measurement until the New Year, it is difficult to be more specific. The depth of snow cover (145 cm at 1620 m) in January was 210% higher than average. January 2012 was also abnormally mild, but then a cold snap hit Europe, with temperatures as low as −25 °C in Saint-François-Longchamp (1620 m) for three weeks. This was followed by a sudden mild spell and rainfall at medium altitudes, which reactivated snow gliding and widespread wet-avalanche activity, especially after 23 February, when the freezing point rose to 2000 m, then 3000 m on 29 February, and 3300 m on 2 March.

1.2. 2 March 2012 Avalanche

The avalanche occurred on 2 March 2012, at 15h15. In the starting zone, the snow cover thickness ranged from 30 cm to 300 cm, with an average close to 250 cm. Freezing during the night had been superficial: over 80 cm of the upper snow layer was almost cohesionless. The average density was estimated at 400 kg m^{-3}. The snowpack (mostly made of rounded grains) exhibited no weak layer, but rested on a base ice layer of 5 cm. Earlier in the season, the sudden heavy snow load and mild temperatures had resulted in the formation of numerous glide cracks on south-facing slopes below 2500 m, some of which gave rise to glide avalanches.

The 2 March avalanche originated from an apparently consolidated glide crack which had started to develop in early January. The slope angle was quite steep just below the ridge line (40° between 2100 m and 2050 m), but quickly became gentler (30° between 2050 m and 1950 m). A thick slab started to slip on the grassy slope. The initial surface was approximately 1.1 hectares and the mean thickness was close to 2.5 m, which led to an initial snow volume of about 25,000 m^3. Figure 1 shows the starting zone, entire avalanche path, and the chairlift whose lower station was damaged by the avalanche. Field investigations showed that the slab slid slowly because of the ground's roughness (irregular topography, widespread rhododendron bushes). Part of the slab slid a few meters and came to a halt on a rather steep slope (35° to 40°). Figure 2 shows the upper boundary of this slab. The other part dislocated into blocks of different sizes, which slid downward in the form of a steady stream. As shown by Fig. 1, many blocks and slab chunks deposited quickly after their release, indicating that flow resistance was significant relative to gravitational forces, but the bulk of the mass continued its course down to the lower station of the Lauzière chairlift (1900 m).

Several factors explained the fairly long runout distance. First, the glide avalanche followed a thalweg, which limited its lateral spread. The

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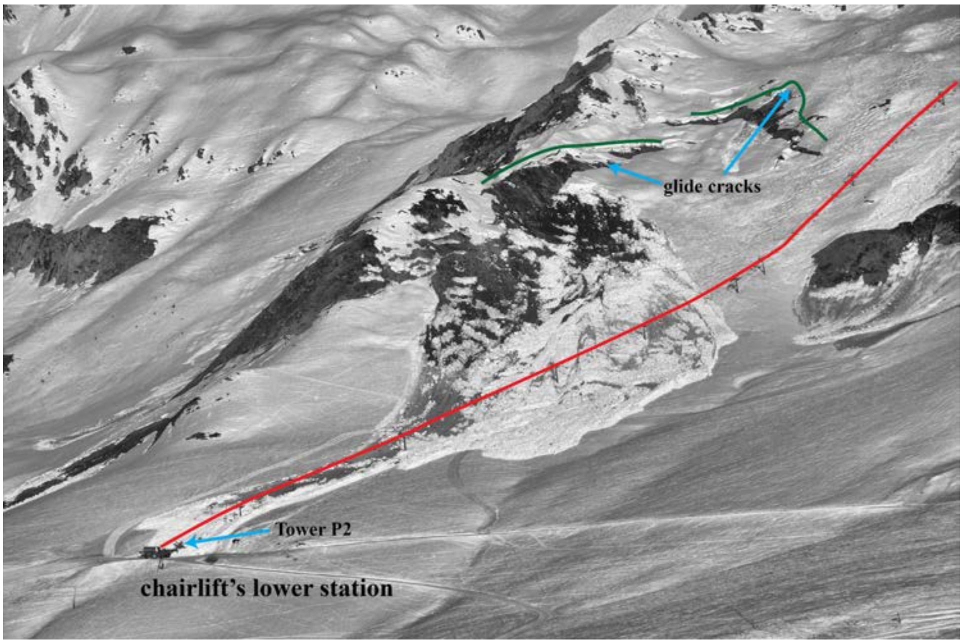

Figure 1. View of the avalanche path and the chairlift hit by the avalanche at Saint-François-Longchamp (photograph taken on 4 March 2012).

avalanche width did not exceed 40 m. In the lower part of its path, the glide avalanche eroded the snow cover, and by sinking gradually into it, the mass of snow mobilized increased. As shown by Fig. 3, the left-hand border (in the direction of flow) was a 1-m deep snow wall, which contributed to channeling the flow. Second, ground friction was replaced by snow friction, and so it was reduced as a result of a thin lubricating layer at the base of the flow. Fourth, the slope angle remained sufficiently steep in the lower part of the path: 19° between 1900 m (point of farthest reach) and 1915 m (upper altitude of the deposit), but 16° on average between 1900 m and 1935 m—these can be compared with the avalanche path's mean slope angle: 22° between 1900 m and 2115 m. A tourist-made video (see the movie on http://videos.tf1.fr/jt-we/2012/un-telesiege-detruit-par-une-avalanche-7035278.html or http://www.youtube.com/watch?v=8eXKi6aiGlg) showed that the avalanche slid slowly at a mean velocity of 1 $\mathrm{m\,s^{-1}}$.

The sudden change in slope as the avalanche hit the lower station of the Lauzière chairlift (1900 m), located on a broad, flat area, caused the avalanche to come to a sudden halt. The snow deposit averaged 7 m in height. Its volume and density were estimated at 3000 $\mathrm{m^3}$ and 500 $\mathrm{kg\,m^{-3}}$, respectively. Whereas none of the towers hit by the avalanche were damaged when it was in its flowing phase, two of the metallic towers (diameter 508 mm) supporting the chairlift departure station were bent at 60 cm above their foundations when the avalanche was in the run-out phase. Back calculations (made by an independent project manager) led to drag force estimates close to 205 kN (equivalent to a mean snow pressure of 61 kPa). Although the chairlift was carrying skiers, and many people were in the close vicinity of the departure station, nobody was injured thanks to a patrolman who quickly stopped the machinery and called for a rescue operation. Figure 4 shows the avalanche deposit near the departure station.

Figure 2. Part of the slab came to a halt after a short slide. The ski pole (135 cm) gives an indication of the snow depth. Photograph taken in the starting zone, on the far right of the upper crack seen in Fig. 1.

This sector of the ski area has been in use for more than 25 years and is watched over by patrolmen (the chairlift was built in 1987). No significant avalanche had been observed on the slope above this lift (apart from surface sluffs after snowfalls or in spring when snow starts loosing cohesion). This area had been noted as 'potentially prone to avalanches' in the *the Localisation Map of Avalanche Phenomena* avalanche map edited by IRSTEA (Institut de recherche en sciences et technologies pour l'environnement et l'agriculture, a French public research institute). Slope angles were not particularly low, but the fact that a small snow volume was able to travel a fairly long distance on relatively mild slope (22° on average) and at low velocity is quite amazing.

2. GLIDING SNOW ACCIDENT IN CAUTERETS

2.1. Location and Meteorological Conditions

Cauterets is a village and ski resort located in the Pyrénées-Atlantiques, located 10 km north of the Franco-Spanish border and approximately 150 km southwest of Toulouse. The village is situated at 950 m in the upper Gave du Pau valley, at the foot of the Vignemale mountain (3298 m), a moist region with a total precipitation exceeding 1500 mm at 1500 m asl. In spite of its proximity to the Mediterranean Sea, the climate is essentially under the influence of Atlantic storms, which bring abundant quantities of rain and snow.

Figure 3. Tower hit by the avalanche (with no damage) and left-hand border of the avalanche track for the Lauzière chairlift at Saint-François-Longchamp.

Figure 4. Lower station hit by the glide avalanche at Saint-François-Longchamp.

The Lys cable car is the main mode of transport between the village and the ski area (1850 m). It crosses several open slopes called "Mans Arrouy," whose salient features are their steep slope (36° on average over an elevation drop of 450 m), an absence of vegetation (except for a few trees at the toe of the slope), little notable relief, their exposition to the sun (south to south-east), and their medium altitude (1310 m to 1850 m). The ridge line, the river at the bottom, and a few thalwegs due to torrential erosion are the only features that provide any structure to the terrain and may impart some preferential directions to snow flow. Due to the slope steepness, avalanche activity is widespread and frequent after snowfall or whenever the snow starts to lose cohesion under the effects of the sun or rising temperatures. Most of these avalanches are full-depth avalanches that descend the entire slope down to the Gave de Cambasque River (1310 m), and thus leave large surfaces of ground free of snow. Figure 6 shows the site. Three towers (referred to as P9, P10, and P11) are exposed to avalanches. They were built to resist impact pressures as large as 60 kPa up to a height of one meter (the force moment at the service limit state was 2133 kN·m).

The winter 2012-13 will be remembered as a winter of the extremes: extreme snowfall and snow

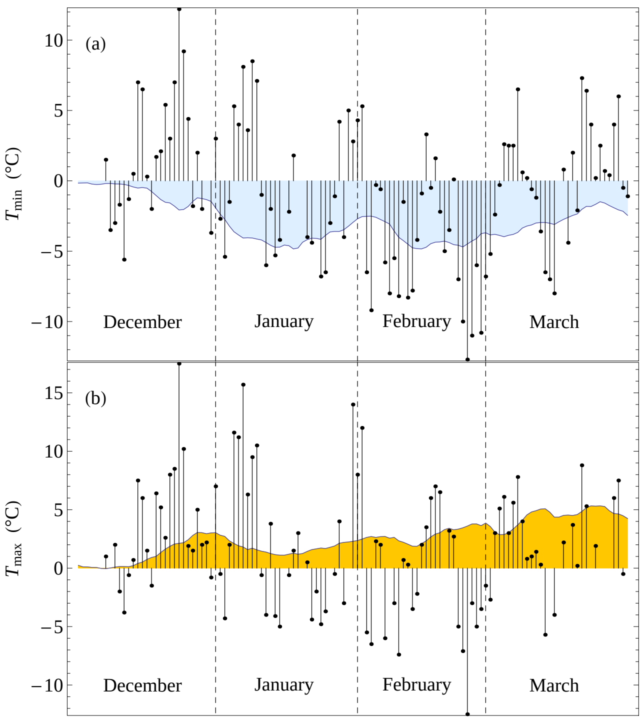

Figure 5. (Upper panel) Change in the temperature measured at 6 a.m. near the upper station of the Lys cable car (1850 m). (Lower panel) Change in the temperature measured at 1 p.m. The solid lines show the temperature evolution averaged over the last decade.

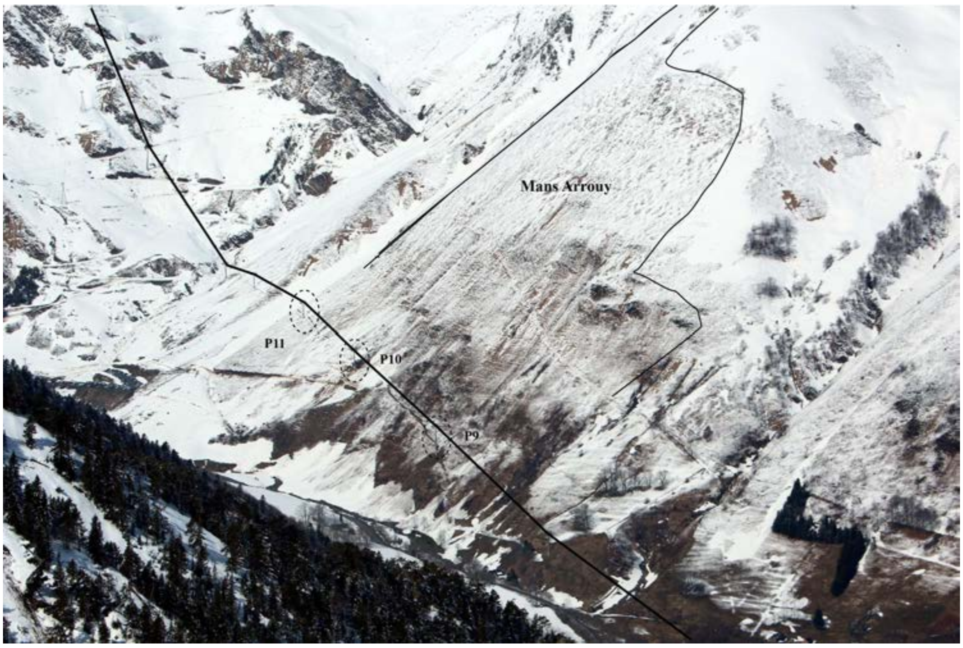

Figure 6. View of the site in late spring 2013. Snow deposits at the toe of the Mans Arrouy slopes are still visible. Tower P10 was the one damaged by gliding snow on 16 February 2013.

depth, extreme mild spells and rainfall. Between 1983 and 2013, the mean annual snowfall was 515 cm, while the mean depth of snow at 1850 m asl was 159 cm. In February 2013, the snow cover was 4.3 m deep at 1850 m. The total snowfall over 1 month (15 January to 15 February) exceeded 10 m at 1850 m asl. Snow came in waves with intense precipitation rates (3 snowfalls with more than 90 cm/day) or long durations (440 cm in 14 days), with the rain line varying around 2000 m. With 1014 mm of precipitation at 950 m during the winter season (January to March) and with the snow total from early December to late March reaching 12.15 m at 1850 m, winter 2013 broke records at Cauterets.

Due to the occurrence of three mild spells (mid December 2012, early and late January 2013), temperatures were exceptionally high some nights. As shown by Fig. 5, the temperature did not reach freezing point during the nights from 4 to 9 January 2013 (and during 5 other nights) at 1850 m asl. At 6 a.m. on the morning of the accident, the temperature at 1850 m was measured at +3.3 °C. When comparing these temperatures with the mean trend, what sticks out is the number of anomalies, with deviations as large as +12 °C relative to the mean trend.

Alternating periods of intense snowfall and rainfall caused significant avalanche activity on the Mans Arrouy slopes during the snow storm of early February. Numerous glide avalanches were observed. Deposits of compact snow accumulated at the toe of the slope. These deposits also contained lots of dirt and debris as well as ice chunks. Near tower P10, the resulting 4.8 m deep snowpack was made up of accumulated snow and avalanche deposits. Its depth-averaged density was estimated at 650 $\mathrm{kg\,m^{-3}}$ (values as high as 680 $\mathrm{kg\,m^{-3}}$ were measured at the base of the snow cover). As a result of this glide avalanche activity, the Mans Arrouy slope was a patchwork of snow slabs and terrain cleared of snow.

2.2. Accident of 16 February 2013

In the days preceding the accident, a glide crack was observed 60 m above tower P10, near the upper limit of the slab (see Fig. 7). Figure 8 gives the dimensions of the tower and the snowpack features. Glide velocity was estimated at 40 cm/day before the accident, but was much higher on the morning of 16 February: the slab slid a distance of 2 m within 12 h, i.e. a velocity of 4 m/day, which is a 1000 times the usual gliding rate on a grassy slope. On that day, snow gliding caused a sudden tipping of P10 and the machinery to halt. The neighboring towers were not damaged. On 17 February, the tipping angle reached 10°. The tower was reinforced using cables, and its foundations were cleared of snow (see Fig. 9). Field observations revealed that both shearing and gliding had taken place, but gliding was the predominant process. Once the lower part of the tower had been cleared of snow, the slab stopped gliding. In many places, a gap as large as 40 cm was observed between the basal ice layer of the snow cover and the ground, indicating that ground friction resistance was reduced. Back calculation from observed dam-

Figure 7. Side view of tower P10 on 18 February 2013. The glide crack is about 60 m above the tower. A track was dug for the rescue operation. Courtesy of J.-L. Pons.

age gave values of 1420 kN of drag force (horizontal component) and 200 kPa for the depth-averaged snow pressure.

3. GLOBAL WARMING AND WARMER SNOWPACK

Recent field surveys have shown that mountain regions are highly sensitive to climate change. In Europe, snow depth has been decreasing over recent decades, especially at low and medium altitudes (below 2000 m), as a result of lower precipitation and/or higher temperatures [*Föhn*, 1990; *Lartenser and Schneebeli*, 2003; *Scherrer et al.*, 2004; *López-Moreno*, 2005; *Beniston*, 2005; *Martin and Etchevers*, 2005; *Durand et al.*, 2009; *Valt and Cianfarra*, 2010; *Serquet et al.*, 2011]. Global and regional climate models predict substantial warming and shorter snowpack duration, particularly for southern Europe's mountain ranges [*López-Moreno*, 2005; *Vicente-Serrano et al.*, 2007; *López-Moreno et al.*, 2009, 2011; *Gobiet et al.*, 2014]. Locally, substantial spatial and seasonal variability is also expected owing to topography's role in atmospheric circulation [*López-Moreno and Beniston*, 2009]. In northern Spanish mountain ranges and Italy, snow precipitation is predicted to decrease significantly in the coming decades [*López-Moreno et al.*, 2011; *Soncini and Bocchiola*, 2012], whereas the opposite trend is predicted for the northern Alps [*Beniston*, 2006; *Schär and Frei*, 2005; *Frei et al.*, 2006; *Rajczak et al.*, 2013].

3.1. An Increase in the Wet-Snow Avalanche Activity?

Some studies have provided evidence for a decreasing trend in the run-out distances of extreme avalanches [*Eckert et al.*, 2010a, 2013] and in the intensity of extreme rainfall in recent years [*Blanchet et al.*, 2009; *Durand et al.*, 2009; *Marty and Blanchet*, 2012]. Other investigations, however, have come to the opposite conclusion, i.e. a relative stability in the potential for avalanche damage since the late 19th century [*Schneebeli et al.*, 1997, 1998]. For instance, in France, in recent years, heavy snowfall led to a catastrophic avalanche situation in Montroc (February 1999, Chamonix-Mont-Blanc), where twelve people were killed in their dwellings [*Ancey et al.*, 2000; *Rousselot et al.*, 2010], and to another in the southern French Alps in 2008 [*Eckert et al.*, 2010b]. Both cases were characterized by heavy snowfall, strong winds, and dry-snow avalanches. Such disasters seem to have occurred on a regular basis over the last century, with a significant accident in the Alps every 6 or 7 years on average. This has been independent of any rise in air temperature [*Laternser and Schneebeli*, 2002; *Höller*, 2009].

The origins of this regular pattern have been discussed in relation to the characteristics of global atmospheric circulation and their decade-scale variations, as illustrated by the cycles of the North Atlantic Oscillation or other indices [*Keylock*, 2003; *Esteban et al.*, 2005; *Vicente-Serrano et al.*, 2007; *García et al.*, 2009; *García-Sellés et al.*, 2010; *Terzago et al.*, 2013]. Perceived increases or decreases in snowfall and associated avalanche situations over time are often conditioned by the variables used and the time span considered. As a consequence, it may be difficult to distinguish between the effects of long-term climatic changes and those induced by lower frequency variability. Some studies conclude that there is a clear trend emerging from the precipitation records: the undisputed evidence of increasing air temperatures over the last century leads some to consider that the frequency of extreme snowfalls has markedly reduced [*Marty and Blanchet*, 2012]. Yet, other studies draw attention to the low-frequency variations (over several decades) of the weather patterns controlling air temperature and snowfall in the Alps, which may explain the increase in the frequency of winter mild spells [*Beniston and Jungo*, 2002; *Zampieri et al.*, 2013].

The most recent investigations into wet-snow avalanche activity show considerable variability in their relative frequency [*Baggi and Schweizer*, 2009; *Pielmeier et al.*, 2013]. A survey in the Swiss Alps for the period between 1951 and 2012 revealed that in the 1960s, wet-snow avalanches represented 20% to 30% of the total number of observations, but this figure had increased to 50% in the late 1980s. However, this trend seems to have been reversed in the late 1990s. Today, wet-snow avalanches represent 30% to 40% of observations [*Pielmeier et al.*, 2013]. The authors of this survey did not exclude the possibility of a bias introduced by a change in the observation protocol, but independently of this issue, the study provides further evidence for a low-frequency variation (over a few decades) in snow and avalanche conditions.

From this perspective, there is no clear indication of a significant change in the avalanche activity in the Alps over the last decade. However, there is growing concern about the significant increase in

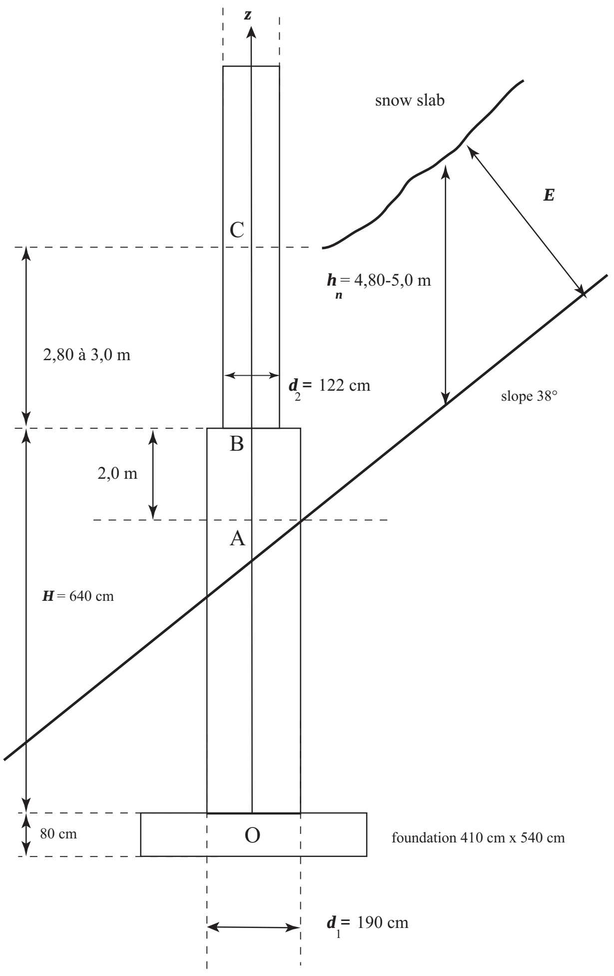

Figure 8. Sketch of tower P10 of the Lys cable car at Cauterets.

Figure 9. View of the tower taken from above on 18 February 2013. A wire was stretched to stabilize the tower pushed over by the sliding slab. Courtesy of J.-L. Pons.

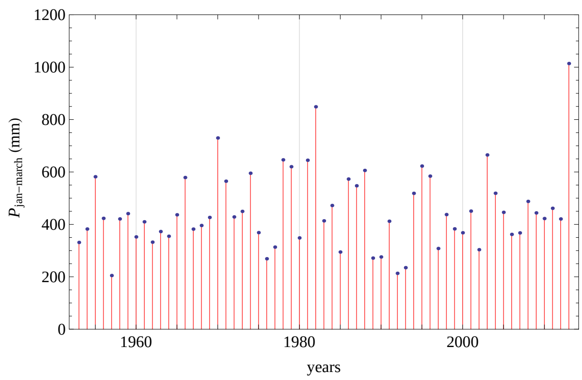

Figure 10. Variation in monthly total precipitation in the village of Cauterets (950 m) from January 1953 to April 2013.

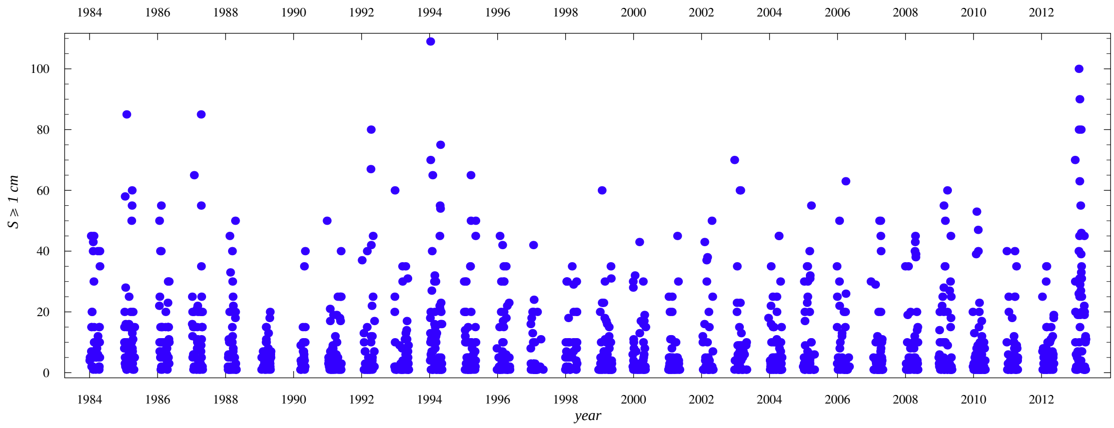

Figure 11. Snowfall distribution at Cauterets 1850 m from December 1983 to April 2013. Each dot represents a snowfall.

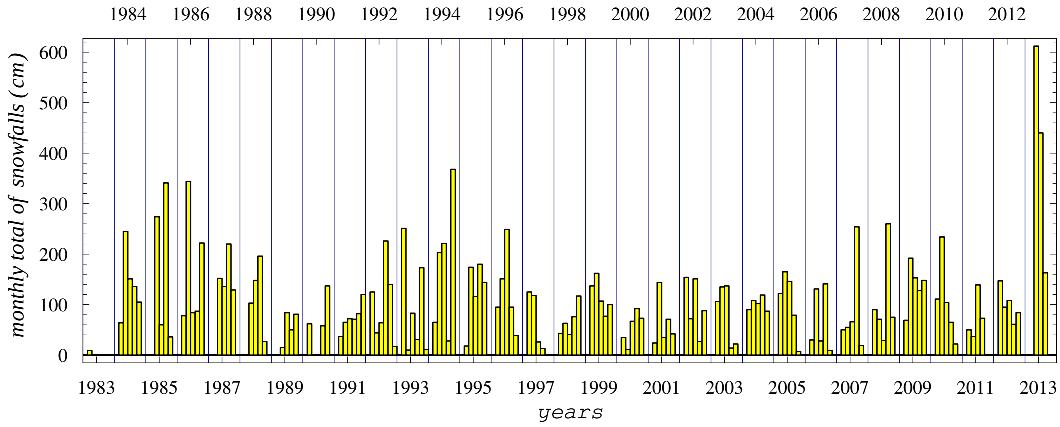

Figure 12. Variation in the monthly snowfall total at Cauterets (1850 m) from December 1983 to April 2013.

the number of accidents due to gliding snow in ski resorts. This concern, expressed by ski industry professionals, is also reflected by the substantial increase in the number of ski lifts damaged since 2011. The cause of this increase may lie in warmer ground, which modifies the boundary conditions as snow cover starts to spread and increase early in the season. As far as we are aware, there are, for the moment, few data confirming or refuting this assumption. The Saint-François-Longchamp case is insightful as no gliding snow events were observed between 1987 (when the chairlift was built) and 2012 (since when it has been damaged twice).

3.2. An Increase in the Snow Precipitation?

In the literature on climate change in mountain areas, authors have analyzed long time series of precipitation and snow depth data in order to draw out any trends induced by global warming. For the Pyrénées, *Vicente-Serrano et al.* [2007] found that the second half of the 20th century was characterized by a reduction of the number and volume of precipitation events, but an increase in the intensity of extreme events, especially in autumn, even though these occurred at a lower frequency.

We analyzed the situation at Cauterets regarding the volume of snow precipitation and the occurrence of extreme events. We were faced with the difficulty of finding long time series for this high-altitude area. The ski resort did not monitor snowfall on a regular basis before December 1983. From that date onward, we had a time series comprising snowfall, snow depth, air temperature, etc., at 1850 m a.s.l. A longer time series was available for the village of Cauterets at 950 m. A second difficulty was the determination of the key meteorological variables governing gliding snow events. As explained in the description of the conditions prior to the accident (see § 2), several processes were involved: heavy snowfall, a fluctuating rain/snow limit, an accumulation of snow and debris transported by previous avalanches, and succession of cold and mild spells. As the period of return is usually defined for univariate random processes and not multivariate ones, it is difficult to quantify the probability of occurrence of the combination of processes that led to the damage incurred by the chairlift.

Figure 11 shows the depth distribution of daily snowfalls from 1983 to 2013. The striking point is that whereas 2013 did not break the total snowfall record, there was an unprecedented sequence of heavy snowfalls (more than 60 cm per day). The consequence was that total snow depths reached unusually high levels, as shown by Fig. 12. A monthly total as high as 600 cm was recorded in January 2013 (the average total is 73 cm per month). However, we can also look at the equivalent water content and take a closer look at total precipitation (snow and rain) in the village of Cauterets. Figure 10 shows the distribution of the total seasonal precipitation (January to April) in the village from 1953 to 2013. Winter 2013's total of 1014 mm of precipitation proved to be the highest value, but the deviation from the other extreme values or the overall average is less marked than for that year's snowfall totals at 1850 m. A similar observation can be made with the snow depth (at 1850 m): 2013 showed the deepest snow levels, but it was in continuity with previous extreme values recorded at this altitude.

Figures 13 to 15 show the variation of the yearly maxima as a function of the period of return for the seasonal snowfall total (at 1850 m), the seasonal precipitation total (at 950 m), and the snow depth (at 1850 m). They report both the data and the theoretical probability, which is an extreme value distribution:

$$P = \begin{cases} \mu - \frac{\sigma}{\xi}\left[1 - \left(-\ln\left(1 - \frac{1}{T}\right)\right)^{-\xi}\right] & \text{if } \xi \neq 0, \\ \mu - \sigma \ln\left[1 - \ln\left(1 - \frac{1}{T}\right)\right] & \text{if } \xi = 0, \end{cases} \tag{1}$$

where T denotes the period of return, P is the quantile, μ, σ, and ξ are the distribution parameters; the case $\xi = 0$ corresponds to the Gumbel law. The distribution parameters were adjusted using Bayesian inference and yearly maxima [*Coles*, 2001]. Figures 13 to 15 show both the extreme value distributions (with ξ adjusted on the data) and the Gumbel law (by forcing $\xi = 0$), since the latter is often used in engineering studies.

The 1014 mm of precipitation in the village from 1 January to 31 March 2013, gave a period of return of 90 years. At higher altitudes (1850 m), the snow total was associated with a period of return of 60 years. The maximum snow depth at 1850 m was 4.3 m (late February 2013), which corresponds to a period of return of 50 years. The snow storm between 2 and 15 February 2013, dumped 440 cm of snow at 1850 m (period of return 70 years). On shorter time scales, intense snowfalls also occurred, with daily totals reaching 100 cm (corresponding to a period of return of 20 years). A closer look at Figs. 13 and 14 shows that the 2013 precipitations were extreme events, but they showed some continuity with previous events. From this simple examination of univariate processes on a single case, it is difficult to draw firm conclusions about an increase of extreme precipitations. Within the framework of extreme value theory, assuming stationary climatic conditions leads to periods of return for the 2013 event which are in line with observations.

3.3. Period of Return

The notion of the period of return is central to modern risk management techniques. For snow avalanches, like other multivariate processes, it gives rise to numerous problems [*Chernouss and Fedorenko*, 2001; *Keylock and Barbolini*, 2001; *Barbolini et al.*, 2003; *Ancey et al.*, 2004; *Bozhin-*

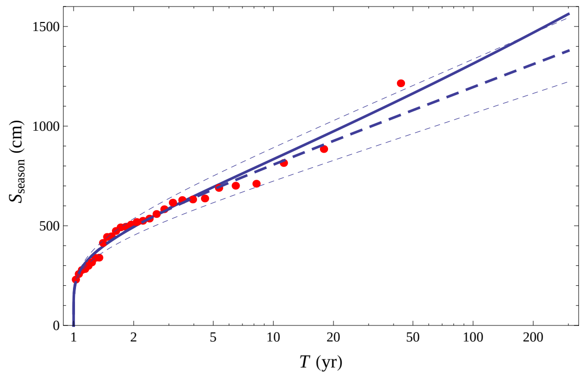

Figure 13. Seasonal snowfall total (from December to April) as a function of the period of return at the Cauterets resort (1850 m). The thick dashed line shows the Gumbel law and the thin dashed lines represent the 95% confidence interval. The thick solid line shows the extreme value (Fréchet) distribution. The dots represent the yearly maxima. Parameters: $\mu = 432.7$ cm, $\sigma = 166.5$ cm, and $\xi = 0.07$ for the extreme value distribution; $\mu = 433.4$ cm and $\sigma = 165.6$ cm, for the Gumbel distribution.

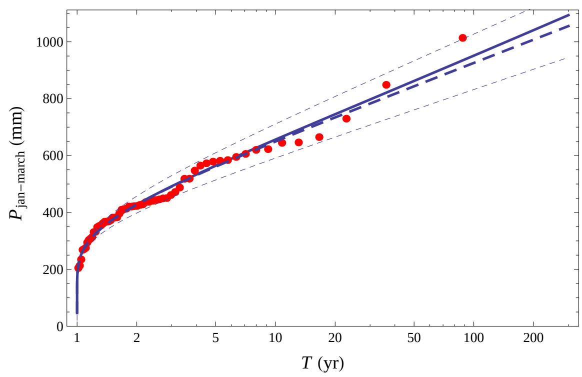

Figure 14. Seasonal precipitation total (from January to March) as a function of the period of return in the village of Cauterets (950 m). The thick dashed line shows the Gumbel law and the thin dashed lines represent the 95% confidence interval. The thick solid line shows the extreme value (Fréchet) distribution. Parameters: $\mu = 384.5$ mm, $\sigma = 118.1$ mm, and $\xi = 0.02$ for the extreme value distribution; $\mu = 385.5$ mm and $\sigma = 117.7$ mm, for the Gumbel distribution.

skiy, 2004; *Cappabianca et al.*, 2008; *Bründl et al.*, 2010; *Eckert et al.*, 2012]. To work around these problems, expedients such as the method developed in the Swiss guidelines [*Salm et al.*, 1990] have turned out to provide robust estimates of the main features of extreme avalanches when these occur due to heavy snowfall. In the context of glide avalanches analyzed here, not only are numerous processes at work, but there is also growing evidence of the potential effects of climate change on precipitation, and thus these empirical solutions may prove defective. There is now a greater awareness of the limits of current approaches to risk management in mountainous areas [*Bründl et al.*, 2010; *Papathoma-Köhle et al.*, 2011; *Fuchs et al.*, 2013]. One line of research should clearly aim for a more robust definition of the period of return [*Eckert et al.*, 2012; *Rootzén and Katz*, 2013].

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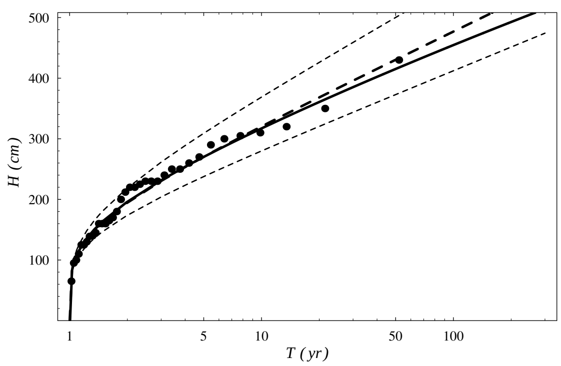

Figure 15. Snow depth as a function of the period of return at the Cauterets resort 1850 m. The thick dashed line shows the Gumbel law and the thin dashed lines represent the 95% confidence interval. The thick solid line shows the extreme value (Weibull) distribution. Parameters: $\mu = 171.8$ cm, $\sigma = 67.9$ cm, and $\xi = -0.05$ for the extreme value distribution; $\mu = 170.6$ cm and $\sigma = 66.7$ cm, for the Gumbel distribution.

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