

Tree-Ring Based Reconstruction of Past Snow Avalanche Events and Risk Assessment in Northern Gaspé Peninsula (Québec, Canada)

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1 Introduction

Although frequencies of avalanches are much higher in the Canadian Cordillera, archival research, coroner's investigations and newspaper searches revealed the occurrence of many snow avalanche events in eastern Canada (Liverman et al. 2001; Héту and Brown 2006; Héту et al. 2008), highlighting the great destructive capacity of snow wasting even on short slopes. Historical records indicate that avalanches are the second most deadly natural hazard in the Province of Québec with over 71 victims between 1825 and 2008 (Héту et al. 2008). Snow avalanches primarily affect backcountry recreational activities in highlands but also dwellings and transportation corridors in inhabited areas (Germain 2005; Héту 2007; Héту et al. 2008). It is therefore a priority to improve our knowledge of this phenomenon for better management of this deadly natural hazard, particularly regarding the following topics: (i) recognition of snow-avalanche prone areas and hazard mapping. This implies the assessment of predisposing factors (local topography, slope aspect, vegetation) in the specific context of Québec where deadly avalanches have mainly occurred on very short slopes outside mountainous areas (Héту et al. 2008); (ii) the frequency-magnitude of snow avalanches, including extreme events like the

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avalanche event which occurred in Kangiqsualujjuaq (east of Ungava Bay) in 1999 (nine fatalities and 25 injured); and (iii) the specific climatic and meteorological conditions responsible for avalanche occurrence and variability for the last century which is critical for the understanding of present and future avalanche activity in the context of climate change (Larocque et al. 2001; Boucher et al. 2003; Dubé et al. 2004; Héту and Bergeron 2004; Germain et al. 2005, 2006; Héту 2007; Héту et al. 2008; Germain et al. 2009).

In the Province of Québec, there is no structural protection nor any daily forecasting procedures to reduce avalanche risks, as compared with western Canada (Hägeli and McClung 2003), France (Jomelli et al. 2007) or Switzerland (Salm 1997), where prevention plans against avalanche initiation and snow avalanches are available and provide land-use prescriptions to minimize the impacts of avalanches. However, because backcountry recreational activities in the Chic-Chocs Mountains (Gaspé Peninsula) are growing rapidly (Boucher 2000), the Haute-Gaspésie Avalanche Center (Centre d'avalanche de la Haute-Gaspésie) now produces bi-weekly bulletins to inform backcountry users on snow conditions and avalanche risks. However, linking snow avalanche activity and weather conditions using standard forecasting methods (Laternser and Schneebeli 2002; Hægeli and McClung 2003; Jomelli et al. 2007) is a difficult task in this region because of the lack of avalanche surveys and the scarcity of weather stations providing long-term records, both at low and high elevations. On the other hand, tree-ring data from several sites spread over large areas may help in understanding the spatio-temporal variations of avalanches (Butler and Sawyer 2008; Stoffel and Bollschweiler 2008; Germain et al. 2009). In that respect, ~10 years ago we started a long-term research program on snow avalanches in the Chic-Chocs Mountains. The objectives can be stated as follows:

1. To provide a tree-ring-based chronology of snow avalanches (frequency-magnitude) in several avalanche paths, particularly high-magnitude snow avalanches
2. To outline specific conditions responsible for avalanche occurrence in low-elevation coastal valleys but also in the alpine-subalpine highlands of the Chic-Chocs Mountains, two areas with contrasting climatic conditions and vegetation cover but significant avalanche hazard
3. To establish a regional tree-ring database based on the study of several avalanche paths, which will allow the assessment of the role of regional (climate and weather conditions) versus local (topography, slope aspect, forest cover and disturbance) factors in avalanche initiation
4. To test and evaluate various sampling procedures and statistical techniques to enhance dendrogeomorphological methods for the study of snow avalanches

Tree-ring analysis has been used for the study of several geomorphic and geological phenomena (cf. Shroder 1980; Solomina 2002), but its accuracy has yet to be investigated (Butler and Sawyer 2008; Stoffel and Bollschweiler 2008), with regard to the appropriate sample size and number of tree responses needed for the recognition of past events. Our research program on snow avalanches in the Chic-Chocs Mountains has focused on appropriate sampling design and statistical methods.

Many efforts were devoted to the evaluation of different types of responses, sample sizes, and the minimum number of samples required for the recognition of past avalanche events.

After a brief description of the study area, we describe methodologies and statistics used so far and summarize results from coastal and highland sites. Subsequently we address methodological issues, stressing the contribution of each method and its usefulness for risk assessment. Problems raised by tree-ring-based studies of snow avalanches are also discussed. Finally, some areas where new developments are needed are outlined.

2 The Study Area

The Chic-Chocs highlands and the coastal valleys near Mont St. Pierre are located in the northern Gaspé Peninsula (Fig. 1). In the mountains, snow avalanches affect mainly backcountry skiing whereas in the low-elevation coastal valleys, snow avalanches may reach roads and affect the transportation system for several hours or days. Clearly there is a need for good quality data on the frequency-magnitude of snow avalanches in this context.

The climate of the Chic-Chocs Mountains is complex largely due to orographic effects and the influence of oceanic air masses on precipitation and temperature, which results in frequent thermal inversions and high cloudiness ($\geq 70\%$, Gagnon 1970).

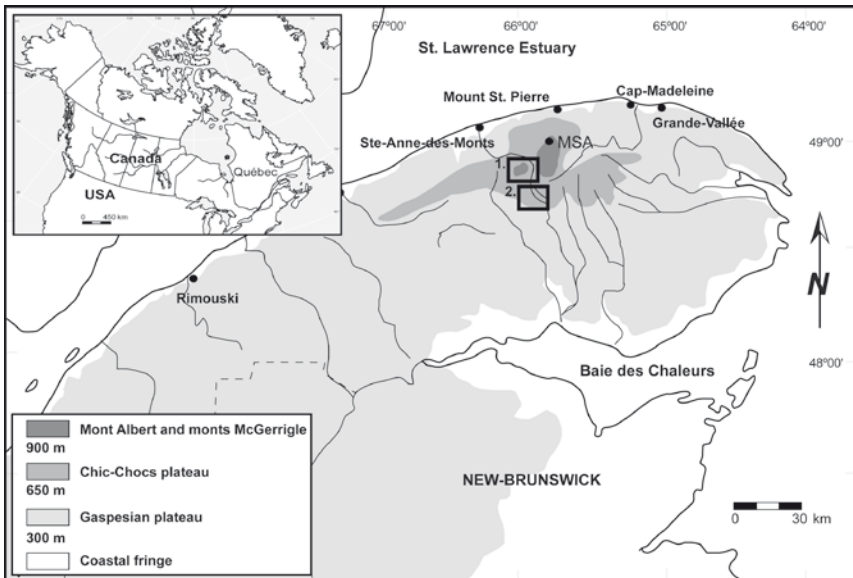


Fig. 1 Location of the study areas in the northern Gaspé Peninsula

Rain can occur in any month during the snow season, even on the highest summits. The mean annual temperature ranges from +3°C at sea level to -4°C at 1,200 m elevation (Gray and Brown 1979). The annual precipitation ranges from 800 mm at sea level to 1,600 mm in the mountains, with 40% falling as snow.

The pattern of snow accumulation is very different in the coastal valleys compared to the Chic-Chocs highlands. In the low-elevation valleys, avalanches occur on small, open patches along forested slopes; elsewhere, strong winds blowing on these scree slopes often result in snow accumulation in forest fringes, reducing the probability for an avalanche to release. Moreover, there is no possibility for snow drifting from the wooded plateau to the steep slopes (Germain et al. 2005; Héту 2007) and for snow cornice formation in the upper rock wall. Thus, snow avalanches are climatically controlled and are primarily a response to major snow precipitation events. In the Chic-Chocs highlands, snow drifting by prevailing north-westerly winds favours avalanche activity due to deep snow accumulation and formation of cornices. These differences in the climatic controls of avalanching between coastal valleys and alpine-subalpine environment of the Chic-Chocs are favourable to high-magnitude snow avalanche activity following several weather scenarios (Germain et al. 2009).

3 Methods

Two main sectors in the northern Gaspé Peninsula, without previous records of avalanche events were investigated using tree-ring techniques. Since our objective was to build a tree-ring-based chronology of high-magnitude avalanches, we used the definition based on that provided by Germain et al. (2009, p. 147), namely “a high-magnitude snow avalanche is regarded as one of sufficient size to exceed the normal boundaries of a given avalanche path, characterized by small scattered and generally impacted trees, entering the mature forests downslope”. We thus assumed that high-magnitude avalanche should result in a greater number of damaged trees and consequently a higher probability of being recorded by tree-ring techniques.

The characteristics of tree-ring sampling in the snow avalanche paths studied are presented in Table 1. It should be noted that avalanche years, e.g. 1898, denote the winter of 1897–1898.

3.1 Site Selection, Sampling Design and Laboratory Analysis

3.1.1 Site Selection

The selection of snow avalanche paths for sampling was based primarily on evidence of past large avalanche events deduced from damaged trees. Physical damage included impact scars, broken trees, tilted stems and asymmetrical branch thinning.

Table 1 Characteristics of tree-ring sampling in the snow avalanche paths studied in northern Gaspé Peninsula

Avalanche path		Tree-ring sampling											
Paths	Elevation (m)	Length (m)	Relief (m)	Slope (°)	Aspect	Sampling design ^a	Sampling location ^b	Trees (n)	Cross-sections (n)	Impact scars (n)	Reaction wood (n)	Years ^c	Year of inner rings ^d
Low-elevation coastal valleys													
T-5	375	390	325	>30.0	W	Lateral Tr.	T & R	62	112	41	300	1860	-
T-3	400	-	375	>30.0	W	Long. Tr.	T & R	20	24	0	-	1939	-
RC	400	-	350	>30.0	W	Long. Tr.	T & R	28	34	0	-	1934	-
T-9	500	700	450	>30.0	W	Dispersed	T & R	78	103	116	95	1932	1809
T-10 1	575	450	400	>30.0	SE	Dispersed	T & R	25	39	58	34	1934	1765
T-10 2	575	680	425	>30.0	SE	Dispersed	T & R	27	45	53	64	1947	1897
T-10 3	575	600	425	>30.0	SE	Dispersed	Run out	8	13	11	14	-	1943
T-10 4	575	550	425	>30.0	SE	Dispersed	Run out	5	8	9	7	-	1942
Highlands of the Chic-Chocs range													
Val-1	840	520	240	27.6	NE	Dispersed	Run out	50	78	50	41	1972	1965
Val-3	840	510	240	27.9	NW	Dispersed	Run out	27	42	25	26	1971	1958
Val-4	870	360	190	33.0	NW	Dispersed	Run out	61	82	64	85	1917	1889
Val-7	840	420	205	29.2	NW	Dispersed	Run out	20	84	26	129	1870	1756
Val-8	800	450	230	31.1	NW	Dispersed	Run out	39	82	26	56	1974	1921
MSA	1,100	670	310	27.1	N	Dispersed	Run out	62	72	77	93	1951	1913
HBN	800	665	350	30.4	NE	Lateral Tr.	T & R	62	-	35	207	1895	-
HBS	800	710	350	30.3	NE	Dispersed	T & R	243	436	207	592	1838	1760
Lateral Tr.													
GC	950	320	120	22.6	SE	Dispersed	Run out	10	59	17	171	1908	1813
MA	995	1125	605	23.9	NE	Dispersed	Run out	68	109	93	115	1944	1901
BLS	830	300	160	5533.2	NW	Dispersed	Run out	22	90	45	103	1896	1772
BLN	830	440	240	31.8	N	Dispersed	Run out	25	80	23	122	1938	1827
Slush flow site													
CM	710	1200	200	8.0	SE	Dispersed	T & R	111	-	-	-	-	-

^aSampling design: D = dispersed; Lateral Tr. = lateral transect; Long Tr. = longitudinal transect.

^bSampling location: R = run out zone; T = avalanche track.

^cYears with ≥ 10 individuals.

^dOldest ring dated on the oldest tree for each path.

Some types of damage may induce sprouting of lateral buds that produce new leaders (reiterates). The sites studied included eight avalanche paths on scree slopes in the low-elevation coastal valleys of Mont St. Pierre and Rivière-à-Claude (Fig. 1), plus 12 alpine–subalpine snow avalanche paths and one subalpine slushflow site. Avalanche path accessibility was also considered given the low density of roads in the region.

3.1.2 Sampling

Most trees sampled were located in open or semi-forested run-out zones and along trimlines. At some sites, however, trees were sampled along 1-m wide lateral transects through the lower part of avalanche tracks and run-out zones and along a 1-m wide transect parallel to the long slope profile (Boucher et al. 2003; Dubé et al. 2004). The sample sizes varied from 5–243 trees (1,049 in total, Table 1). Because some study sites were located within a recreational park area, the sampling concentrated on trees showing evidence of multiple events in order to reduce the number of trees sampled. Cross-sectional discs were collected at various levels along the trunk (curve in the stem, scars, base of reiterates, etc.).

3.1.3 Laboratory Analysis

Cross-sectional discs were finely sanded and analyzed under a binocular microscope for the age determination and the dating of growth-ring anomalies. Growth-ring dating was made possible by ring counting along two or three radii. Frost rings and narrow rings were also recorded. To develop our snow avalanche chronologies, we used tilted trees with reaction wood lasting for at least 2 years and trees with impact scars, as these types of damage provided the most reliable evidence for past snow avalanches (Larocque et al. 2001; Boucher et al. 2003; Dubé et al. 2004; Germain et al. 2005, 2009). Drastic changes in the direction of reaction wood were considered as distinct snow avalanche events. Because small-diameter tree stems are highly susceptible to stem deformation on steep slopes (Johnson 1987; Dubé et al. 2004; Germain et al. 2005, 2009), the 20 innermost rings were not considered in the analysis of reaction wood.

Traumatic resin ducts and new leaders developed from dormant axillary buds on the stems or from a branch which shifted from a subhorizontal (plagiotropic) axis to a stem-like vertical (orthotropic) axis were also used tentatively at some sites, in conjunction with other types of response (Larocque et al. 2001; Dubé et al. 2004). Because traumatic resin ducts may form in response to various environmental stresses (defoliation by insects, tree dieback, etc.), they were not useful indicators for avalanche activity. Accurate dating of the initiation of leaders or radial growth release in branches transformed into stem-like structures revealed a 1–8 year time lag for surviving trees to respond to stem damage (Dubé et al. 2004).

3.2 Statistical Treatments of Tree-Ring Data Sets

3.2.1 Scree Slopes in Low-Elevated Coastal Valleys

Our approach was based on the process-event-response developed by Shroder (1978, 1980). For each year t at each site, the avalanche activity index (AAI; 0–100%) was calculated following Shroder’s methodology, which is based on the percentage of responses in relation to the number of trees alive in year t :

$$AAIt = \left(\sum_{i=1}^n Rt \right) / \left(\sum_{i=1}^n Nt \right) * 100\%$$

where R represents the response to an event for year t and N the number of trees alive in year t . For each avalanche path, event-response histograms were produced based on a combination of reaction wood and impact scars evidence. Each stand-scale chronology of high-magnitude avalanches was based on $\geq 10\%$ threshold on the event-response histogram. Only years with a sample size ≥ 10 trees were considered in avalanche chronologies to avoid overestimation caused by low tree numbers in the event-response calculations. Avalanche tracks studied by Dubé et al. (2004) and Germain et al. (2005) were used at the stand scale.

The regional-scale chronology of high-magnitude avalanches for the low-elevation sites was based on $\geq 10\%$ threshold on the event-response histogram, for the three undisturbed stands (T-5, T-3 and RC) on active scree slopes (Dubé et al. 2004). The two disturbed sites (T-9 & T-10) studied by Germain et al. (2005), which originated from fire and logging, were not considered at the regional scale.

3.2.2 Highlands of the Chic-Chocs Mountains

The tree-ring data from alpine–subalpine snow avalanche paths were analyzed using five different statistical methods (Germain et al. 2009). In this paper, however, we focus on the process-event-response developed by Shroder (1978, 1980) using combined tree responses (i.e., impact scars and reaction wood) to avalanche. For this reason, the avalanche chronology presented here differs slightly from that produced by Boucher et al. (2003) and Germain et al. (2009). Each stand-scale chronology of high-magnitude avalanches was also based on $\geq 10\%$ threshold on the event-response histogram.

In order to provide an estimate of the overall avalanche activity in the alpine–subalpine zone, we developed a regional avalanche activity index (RAAI; 0–100%; Germain et al. 2009). For each year t , the RAAI was calculated as follows:

$$RAAI_t = \left(\sum_{i=1}^n AAI_t \right) / \left(\sum_{i=1}^n P_t \right) * 100\%$$

where AAI represents the avalanche activity index for a given avalanche path for year t and P the number of paths that could potentially record an avalanche in year t , with a sample size ≥ 10 trees. Therefore, the AAIs calculated for all active paths were averaged over the total number of paths in a given year t . Because of overestimates created by low path numbers in the response calculations, only years with a sample size ≥ 3 avalanche paths were considered in the RAAI. In order to ensure the representativeness of the RAAI, with regard to high-magnitude avalanche occurrence, the percentage of active avalanche paths (PAAP; 0–100%) for each year was also calculated based on the number of high-magnitude avalanches recorded in year t divided by the number of avalanche paths that could potentially record an avalanche in year t (sample size ≥ 10 trees).

We used a binary stepwise regression model (i.e., specification of avalanche year or not with values of 1 and 0, respectively) to assess the role of regional vs. local factors in avalanche initiation. The regression was carried out with all weather factors until a significant determination coefficient was obtained for a given RAAI threshold value.

3.3 Return Interval and Annual Probability

Tree-ring-based avalanche records allowed us to estimate the return interval (RI) of high-magnitude avalanches for each path. The return intervals calculated are maximum values because of the decreasing sample size and the possible loss of evidence going back in time. Annual probability (AP) of widespread snow-avalanche activity was also calculated and was found to be inversely related to the return interval, as $AP = 1/RI$ (Mears 1992). We also evaluated RI and AP at the regional-scale for both sectors studied.

4 Results

4.1 Low-Elevation Coastal Valleys

In low-elevation coastal valleys in the northern Gaspé Peninsula, two distinct snow-avalanche regimes can be recognized: (i) natural avalanches that occurred on active scree slopes and; (ii) avalanche activity on treed slopes disturbed by fire and logging.

4.1.1 Snow-Avalanche Regime on Active Scree Slopes

Of the three stands studied by Dubé et al. (2004), stand T-5 yielded the longest record of avalanches going back to AD 1860 with a sample size ≥ 10 individuals (Table 1). At stand T-5, years with avalanche activity index values $\geq 10\%$ were

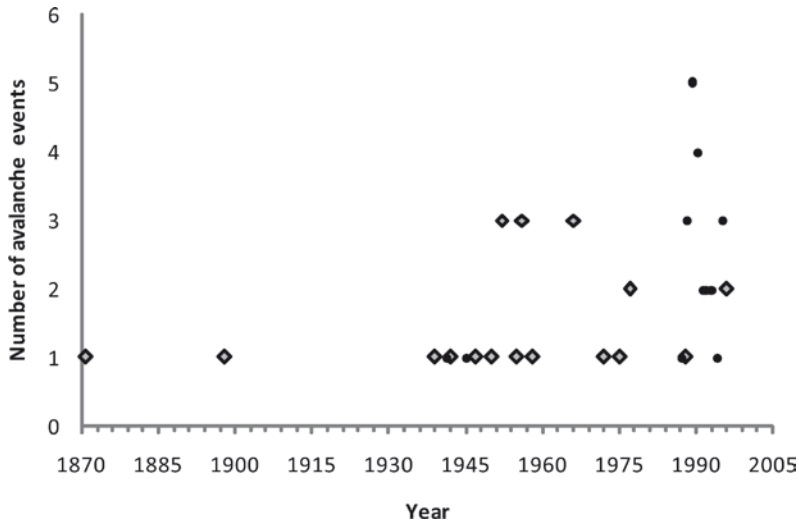


Fig. 2 Number of high-magnitude avalanche events through time on undisturbed scree slopes (light diamonds) and disturbed treed slopes after fire and logging (black dots)

1871, 1898, 1952, 1956, 1966, and 1996. At stand T-3, they were 1947, 1950, 1952, 1956, 1958, 1966, 1972, 1975, 1977, 1988 and 1996. Finally, at stand RC, the seven following years were recorded as avalanche years: 1939, 1942, 1952, 1955, 1956, 1966, and 1977. One should note that at this stand the event-response for the year 1996 was 9%, i.e., just below the threshold value. In spite of the limited temporal extent of avalanche records from T-3 and RC (1939–1997; see Table 1), these two scree slopes yielded a higher frequency of high-magnitude avalanches over the interval common to all three tracks.

At the regional scale, event-responses estimated from the 110 trees sampled in the three stands investigated showed 7 years of high-magnitude snow avalanches ($\geq 10\%$): 1871, 1898, 1952, 1956, 1966, 1977, and 1996. The two oldest years were only recorded at stand T-5, which recorded six out of these seven snow avalanche years (Fig. 2). Of the 5 years after 1939, corresponding to a sample size ≥ 10 trees for all stands, all were recorded at stand T-3 and four at stand RC (Fig. 2).

4.1.2 Snow-Avalanche Activity on Treed Slopes After Fire and Logging Disturbances

At site T-9, the 1938 fire was dated with several fire scars and documented from historical data. This human-induced fire burned 185 ha of forests at the outer edge of the plateau and in the upper part of the slope. The forest opening created local conditions conducive to snow drifting and accumulation of large amounts of snow in the burned, vegetation-free area in the upper steep slope. The tree-ring data indicated two periods of avalanche activity (AAI $\geq 10\%$), i.e., 1941–1945, and 1989–1995 (Fig. 2).

At site T-10, where a clear cut occurred in 1986 on the plateau (~2,250 ha of forest harvested), tree-ring analysis showed high avalanche activity index for the years 1988, 1989, 1990, 1991 and 1995 for avalanche path C-1 and 1988, 1989, 1990, 1992, 1993, and 1995 for avalanche path C-2. Four of the 6 years (1988, 1989, 1990, and 1995) were recorded in both paths. Additional data from two adjacent avalanche paths (C-3 & C-4) also indicated past avalanche events in 1987, 1988, 1989, and 1990. Once again, the forest opening on the plateau created conditions conducive to snow drifting and formation of cornices, as opposed to the three undisturbed scree slopes. The avalanche window in the post-logging site was shorter (<10 years) than that of the post-fire site where avalanche activity was recorded 55 years after fire. This is an indication that avalanche activity after tree removal largely depends on the capacity of woody vegetation to reach heights and density sufficient to control snow drifting and thus avalanche activity.

4.2 Snow-Avalanche Regime in the Highlands of the Chic-Chocs Range

4.2.1 Reconstructed Tree-Ring Local Avalanche Record

The 689 trees sampled in the 12 alpine–subalpine avalanche paths provided 244 avalanche events, which correspond to 86 years. Of the 12 avalanche paths investigated, paths HBS and Val-7 yielded the longest records, going back to 1838 and 1870, respectively. The HBS and Val-7 tree-ring records showed no avalanche activity index $\geq 10\%$ before 1895 in spite of sample sizes ≥ 10 individuals.

High-magnitude avalanches occurred 44 times corresponding to 31 years before 1950, i.e., 56% of all years between 1895 and 1950, compared to 200 times after 1950 corresponding to 49 years, i.e., 98% of all years between 1950 and 2000 (Fig. 3). This means that after 1950 at least one avalanche event was recorded each year, except 1999. Twelve of the 49 avalanche years were recorded on ≥ 6 avalanche paths (50% of all paths investigated, PAAP > 50%): 1969, 1971, 1977, 1981, 1984, 1986, 1988, 1990, 1991, 1993, 1994, and 1995.

On the yearly and decadal scales, the records indicated that high-magnitude avalanche events increased significantly between 1895 and 2000 ($R^2 = 0.55$; $p < 0.0001$), especially after 1950 (Fig. 3). Less than ten avalanche events per decade were recorded between 1900 and 1950 and 40 on average per decade after 1950. Avalanches were twice as frequent during the 1990s (55 occurrences) than between 1950 and 1970.

Tree-ring data from a subalpine site documented by Larocque et al. (2001) indicated the occurrence of three slushflow events in the last century: 1925, 1964, and 1988. A slushflow event was also visually documented in January 2006. The lack of synchrony between snow avalanches and slushflows for 2 years (1925 and 1964, but not 1988 where eight avalanche events were recorded in the alpine–subalpine belt)

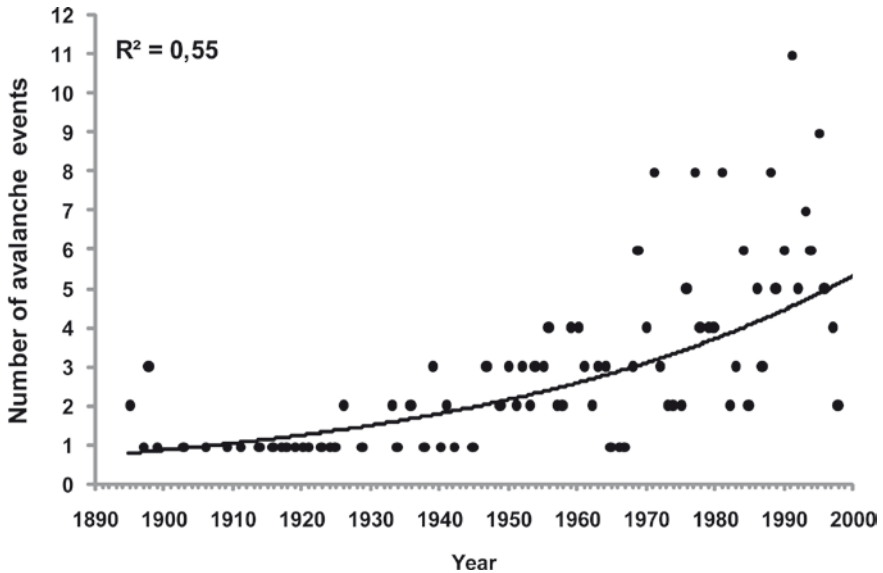


Fig. 3 Number of high-magnitude avalanche events through time in highlands of the Chic-Chocs Range

suggests a strong influence of meteorological conditions in the initiation of slushflows which usually occur in response to increased water content in the snow-pack through rainfall and/or snowmelt (Larocque et al. 2001).

4.2.2 Chronology of Regional Snow Avalanche Activity

Using a RAAI $\geq 10\%$ as a threshold ($R^2 = 0.67$; $p < 0.0001$) for identifying widespread, regional avalanche activity, 19 years of high avalanche activity were identified for the period between 1895 and 2000: 1898, 1936, 1939, 1941, 1965, 1969, 1970, 1971, 1977, 1981, 1984, 1987-1992, 1994, and 1995. Fifteen out of the 19 avalanche years (1898, 1936, 1969-1971, 1977, 1981, 1984, 1988-1992, 1994 and 1995) were also characterized by a high PAAP value ($\geq 33\%$). The PAAP explained more than 63% ($p < 0.0001$) of the variance of the RAAI over the 1895-2000 period. Statistically, the data showed a random scatter around zero with a Durbin-Watson *d*-statistic of 2.0 ($p < 0.01$), which satisfied the assumption of constant variance and non-correlated residuals (Clark and Hosking 1986). This means that 65% of all tree anomalies (damage) were related to high-magnitude avalanche events, likely during major snow avalanche cycles as reported in the western United States (Birkeland and Mock 2001), Switzerland (Hächler 1987), Austria (Höller 2009), and France (Glass et al. 2000). Therefore, the RAAI enabled us to identify 1939, 1941, 1965 and 1987 as high-magnitude avalanche

years at the regional scale, with RAAs of 13%, 11%, 10% and 16%, respectively, in spite of the low number of high-magnitude avalanches recorded those years at the local scale.

4.3 Risk Assessment

4.3.1 Scree Slopes in Coastal Valleys

The return intervals (RI) and annual probabilities (AP) of high-magnitude avalanches on undisturbed scree slopes are presented in Table 2, with RI of 12 years and AP of 12% on average. At stand T-3, RI was short (~5 years) with ~19% probability that avalanches occur in any 1 year. Stand T-5 had the longest estimated return

Table 2 Number of events, return interval, and annual probability (%) of high-magnitude avalanches

Path	N years ^a	N events	RI	AP	1900–1949		1950–1999	
					RI	AP	RI	AP
Low-elevation coastal valleys								
T-5	137	6	22.8	4	0	0	12.0	8
T-3	58	11	5.3	19	–	–	4.8	21
RC	58	7	8.3	12	–	–	9.6	10
T-9	68	9	7.6	13	–	–	7.0	14
T-10 1	66	8	8.3	12	–	–	6.3	16
T-10 2	53	5	10.6	9	–	–	10.0	10
Average	73	8	10.5	12	0	0	8.3	13
Highlands of the Chic-Chocs range								
Val-1	28	6	4.7	21	–	–	–	–
Val-3	29	10	2.9	34	–	–	–	–
Val-4	83	19	4.4	23	6.4	16	3.5	29
Val-7	130	31	4.1	24	16.7	6	1.8	55
Val-8	26	4	6.5	15	–	–	–	–
MSA	49	11	4.5	22	–	–	4.5	22
HBN	103	17	6.1	17	8.3	12	5.4	18
HBS	157	15	10.5	10	50.0	2	4.1	24
GC	92	42	2.2	45	3.2	31	2.2	45
MA	56	14	4.0	25	–	–	4.0	25
BLS	104	27	3.9	26	16.7	6	2.3	43
BLN	62	37	1.7	59	–	–	1.7	59
Average	81	20	5.0	29	16.9	12	3.4	34
Slushflow site								
CM	83	4	20.8	5	25	4	19.0	5

^aYears with ≥ 10 individuals.

interval (~23 years) for a 137-year record. No high-magnitude avalanche was recorded during the first half of the twentieth century, but four occurred after 1950 (Table 2). RC showed intermediate values (~8 years).

At the regional scale, the return interval of high-magnitude avalanches was estimated for the period 1839–1997. Using only those events recorded at two or three stands, RI was estimated as 19 or 12 for all three or two of three sites.

The risk assessment of avalanches after forest disturbances is hard to evaluate for several reasons: (1) forest disturbances, especially fire occurrences, sizes and intensity, cannot be predicted; (2) the frequency-magnitude of avalanches on disturbed treed slopes is closely related to the capacity of woody vegetation to achieve a density and heights for efficient snow drifting control; and (3) RIs and APs may be under-estimated for heavily disturbed areas where specific land-use prescriptions do not exist, especially for logging activities.

4.3.2 Alpine–Subalpine Avalanche-Prone Areas

Depending on the location within the alpine–subalpine belt, RIs varied from 1.7 to 10.5 years in paths BLN (north slope) and HBS (south-east slope), respectively (Table 2), with an average return interval of 5 years. APs varied from 10% to 59% in paths HBS and BLN, respectively, with an average of 29% calculated for all paths.

RIs and APs for the first (1900–1949) and second halves (1950–1999) of the twentieth century were calculated for each avalanche path with an avalanche chronology ≥ 100 years (Val-4, Val-7, HBN, HBS, GC, BLS). RIs decreased sharply after 1950, particularly in the HBS path where only one high-magnitude avalanche event was recorded before 1950 compared to 12 after 1950, which corresponds to a shift of RI from 50 to 4.1 years (Table 2). APs increased after 1950 with values of 29%, 55%, 18%, 24%, 45%, and 43% as opposed to ~16%, 6%, 12%, 2%, 31%, and 6% before. The increase was smaller for avalanche path HBN, with values of 18% and 12% after and before 1950, respectively (Table 2). The number of years for which at least one third of the paths were active (PAAP $\geq 33\%$) also increased after 1970, indicating a significant change in avalanche activity rather than in the preservation of evidence of that activity.

The average interval between high-magnitude avalanche years at the regional-scale was 5.5 years (19 of 105 years). However, 15 (79%) of these 19 years occurred after 1950, which corresponds to a much shorter return interval of 3.3 years (15 of 50 years) and reinforces our interpretation for increased avalanche activity after 1950, both locally and regionally, in the highlands of the Chic-Chocs Range (Germain et al. 2009). Finally, with an average RI of 5 years and AP of 29%, the alpine–subalpine avalanche-prone areas showed shorter RI and higher AP than undisturbed scree slopes in the coastal valleys, with RI of 12 years and AP of 12% on average, and a slushflow subalpine site with a return interval longer than ~20 years calculated for a 83-year period (1925–2008).

5 Discussion

5.1 *Comparison of Snow-Avalanche Regime Between Scree-Slopes in Low-Elevated Coastal Valleys and Alpine–Subalpine Highlands*

In the absence of historical data on avalanche occurrences, our research program provided tree-ring-based records of avalanches for a mountainous region of eastern Québec where avalanches are widespread and frequent. Despite contrasted climatic conditions and vegetation cover, the two sectors studied are characterized by high-magnitude avalanches with great destructive power. In the Chic-Chocs highlands, ~65% of all trees sampled randomly were damaged during the 19 avalanche years identified (Germain et al. 2009). We calculated a RI of 5.5 years for the period between 1895 and 1999, which is very close to that calculated for the Austrian Alps (nine events in more than 50 years) (Höller 2009). This interval is also close to the interval of 5 years reported by Fitzharris (1981) and Johnson et al. (1985) for the Rocky Mountains of western Canada, and 4.9 years reported by Hebertson and Jenkins (2003) for the Wasatch Plateau, Utah (USA).

At the regional scale, no synchronism in high-magnitude avalanche occurrences was apparent between inland subalpine sites and undisturbed scree slope sites in coastal valleys, which suggests the influence of local factors on avalanche activity. The location of the starting zones in open (alpine tundra) or semi-forested (subalpine) areas in the Chic-Chocs highlands creates conditions for snow drifting and cornice formation as opposed to wooded plateaus that dominate scree slopes and vertical rockwalls in the coastal valleys. In this low-elevation environment, strong winds blowing on active scree slopes, which form small open patches along forested slopes, usually decrease the probability of an avalanche to release (Héту and Bergeron 2004). Therefore, the return interval of avalanche events is longer (12 years) and strongly related to snowstorms and snowy winters in coastal lowlands (Dubé et al. 2004; Héту 2007).

The number of avalanche events recorded after 1950 was much higher than during the first half of the century, at both local and regional scales (Figs. 2 and 3). High avalanche frequencies in the western USA during the second half of the twentieth century were also documented using tree-rings. For instance, on the Wasatch Plateau, Utah, Hebertson and Jenkins (2003) recorded 14 avalanche years between 1928 and 1996, ten of them (71%) after 1950. In Glacier National Park, Montana, Butler and Malanson (1985) documented an increase in avalanche frequencies after 1975, compared to the previous 25 years. In the Chic-Chocs Range, the higher frequency of snow avalanche activity seems to be related to an increased climate variability, which creates propitious conditions for snow avalanche release following several scenarios: (1) above-average total snowfall, (2) high-frequency of snowstorms, (3) major rain events and facet-crust development, (4) sequences of freezing rain and strong winds, and (5) early-season weak layers of faceted crystals and

depth hoar (Germain et al. 2009). However, given the possibility of poorer preservation of the earlier record, methodological issues and quality of the data for reconstructing chronologies of snow avalanching are discussed below.

The multi-decadal trend in increased avalanche activity in the Chic-Chocs Mountains and the anticipated climate change, which may favour increased climate variability (frequency of snowstorms, significant rise in air temperature, heavy snowfall and strong winds), should be considered more thoroughly to prevent and mitigate avalanche hazards. For instance, appropriate land management plans should identify safety margins in settlements located in avalanche-prone areas.

5.2 Methodological Issues and Quality of the Data

By utilizing evidence found in living (and, when possible, dead) damaged trees, dendrogeomorphic investigations offer a longer temporal perspective on avalanche frequency and magnitude. On the other hand, avalanches may destroy evidence of earlier events, as well as the susceptibility of a tree to record damage. Therefore, the sampling design, sample size, and tree-ring responses can impact the quality of the record, which also varies with tree species, age and size. Because the tree-ring records from both sectors showed an increased frequency of snow avalanches after 1950, it raises the question of the quality of the data, the influence of sample size, and the threshold value for the acceptance of an avalanche event.

5.2.1 Tree-Ring Reconstruction of High-Magnitude Snow Avalanches or Extreme Events?

Specification of return periods in the run-out zone is the first and most important step for avalanche hazard assessment and zoning (McClung 2000). It is therefore surprising that many studies that dealt with tree-rings for the reconstruction of past snow-avalanches did not clearly state the objectives. Because the distribution of run-out distances in space follows a Gumbel distribution (McClung and Mears 1991), the location of sampled trees may induce significant discrepancies in the evaluation of return periods. We must keep in mind that some avalanches cannot be recorded by trees because snow masses were too small to reach the run-out zone or to cause obvious damage to trees such as impact scars. Conversely, large avalanches can cause extensive damages and high mortality reducing the subsequent potential of tree-ring records (Rayback 1998).

In the Chic-Chocs Mountains, sampling covered the present run-out zone and its immediate forested peripheral area entirely so as to locate distant damaged trees and to minimize the effect of the sampling design. Past avalanche events were confirmed as high-magnitude events by analyzing the location of damaged trees. Hence, we did not focus on extreme events for which damaged trees were only to be found farther down on very gentle slope ($<10^\circ$) and in mature forest stands.

5.2.2 What Are the Best Indicators of Past Snow Avalanche Activity?

To develop snow avalanche chronologies, various tree responses have been used so far. Impact scars, sequences of reaction wood, and growth release or suppression appeared the most useful responses (Burrows and Burrows 1971; Carrara 1979). In the northern Gaspé Peninsula, we used living trees with impact scars and tilted trees with reaction wood, as these tree damage types provided the most reliable evidence of past snow avalanches (Larocque et al. 2001; Boucher et al. 2003; Dubé et al. 2004; Germain et al. 2005, 2009). However, to ensure the reliability of our avalanche records, we opted for the following procedures: (i) the 20 innermost rings were not considered in the analysis of reaction wood because small-diameter tree stems are highly susceptible to stem deformation on steep slopes; (ii) we used sequences of reaction wood lasting for at least 2 years; (iii) a drastic change in the direction of reaction wood was also considered as originating from distinct snow avalanche event, and (iv) when possible, two types of responses or more were used as complementary tools for avalanche reconstruction.

Traumatic resin ducts have also been used successfully as valuable tools for documenting various geomorphic processes by Stoffel et al. (2006) and Casteller et al. (2007). In the Chic-Chocs Range, however, the formation of traumatic resin ducts seemed related to other environmental stresses, namely insect activity causing defoliation during severe epidemics. Larocque et al. (2001) showed that only a few annual rings with rows of traumatic resin ducts were related to avalanche disturbances.

Additional, less well documented tree response types (e.g. as used by Carrara 1979) consist of shoot initiation and radial growth release in branches transformed into stem-like structures, which marks a change in axis direction. However, these responses remain poorly documented. At a stand studied by Dubé et al. (2004), 12 and 11 new leaders were produced 8 and 6 years after the 1956- and 1966-avalanche events, respectively. Therefore, traumatic resin ducts shoot initiation and radial growth release in branches may be used as complementary tools to the main type of responses, namely impacts scars and reaction wood.

5.2.3 What Are the Optimum and Minimum Sample Sizes?

In a recent paper, Butler and Sawyer (2008) argued that a few damaged trees may be sufficient for the development of an avalanche chronology, but 100 such trees would be better. It is clear that the larger the sample size, the higher the probability to record past avalanche events. However, because the avalanche activity index is based on the percentage of responses in relation to the number of trees alive for a given year (following Shroder's method) a very large sample size may increase the noise and make deciphering past avalanche events even more difficult.

The cumulative distribution function (CDF) of avalanche chronologies, which describes the probability distribution of avalanche chronologies for variable sample sizes, were plotted for sites at low-elevation coastal valleys (Fig. 4a) and alpine-subalpine belt in the Chic-Chocs Range (Fig. 4b), respectively. In both cases,

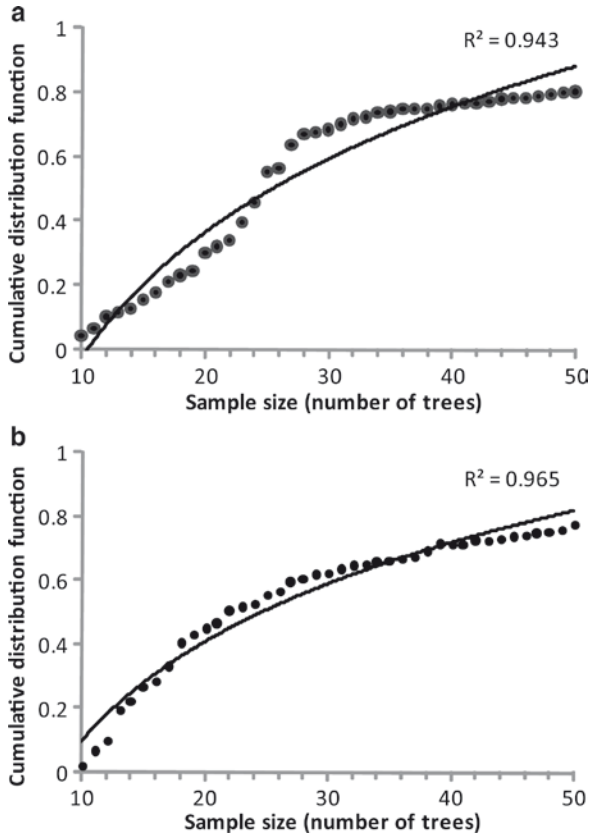


Fig. 4 Cumulative distribution function of avalanche chronologies as a function of sample size for scree slopes in low-elevation coastal valleys (a) and for alpine-subalpine avalanche paths in the Chic-Chocs Range (b)

the data follow a logarithmic law ($R^2 = 0.94$ & 0.97 ; $p < 0.0001$). With a sample size increasing from 10 to 25–30 trees (Figs. 4a and b), the probability to extend avalanche chronologies is high, but with sample size >40 , this probability will increase only slightly, indicating that a good selection of trees for sampling is an important prerequisite for the development of avalanche chronologies. In that connection, the higher avalanche frequency calculated for the period after 1950 in the northern Gaspé Peninsula is not related to the sample size. Indeed, no significant correlations were found between the number of avalanches recorded and the length of the chronologies ($R^2 = 0.30$; $p > 0.05$) and between the number of avalanches and trees sampled ($R^2 = 0.21$; $p > 0.10$), which varied greatly from one path to another.

The sampling design is unquestionably an important issue, but also the location, dendrometric parameters (heights, diameters, presumed ages) and anomalies (damages originating from multi-events) of trees. Table 1 shows the oldest growth ring dated at each avalanche path, which indicates that tree longevity rather than

tree life expectancy in avalanche-prone areas appears to be the main limiting factor for avalanche chronology development. Obviously, the number of old trees decreases back in time, but we argue that a minimum of ten trees is required for calculation of any avalanche activity index. Burrows and Burrows (1971) and Stoffel et al. (2006) used a single tree to conclude past avalanche events. Tree responses for years with <10 trees should be considered as additional pertaining information, but not for chronology building and ensuing calculation of frequencies, return intervals, etc. A single tree is definitely not enough, particularly for risk assessment. When the sample size has to be minimized for some reasons (e.g., recreational or protected areas) sampling should be done so as to maximize the information, by collecting several discs from a limited number of trees (Stoffel et al. 2006; Germain et al. 2009).

5.2.4 What Is the Minimum Number of Tree-Ring Responses for Past Avalanche Event Identification?

One of the main difficulties in tree-ring analysis on trees showing damage from multiple events is to statistically distinguish avalanche events from other types of disturbances (slope or wind effects on stem deformation). Following the approach based on the process-event-response developed by Shroder (1978, 1980), each stand-scale chronology of high-magnitude avalanches is based on the ability to identify growth anomalies in the field, but also on a quantitative threshold value for the identification of avalanche events. Butler and Sawyer (2008) considered that 20% as a minimum number of trees needing to respond in order to invoke an avalanche event was more appropriate than 40% (Butler and Malanson 1985; Butler et al. 1987; Bryant et al. 1989) because of the small size of sampled trees (≤ 12) along some avalanche paths and based on data from historical records of avalanches.

In the northern Gaspé Peninsula, a 20% threshold value is not appropriate given the sample size (average >50) per avalanche path. With a 20% threshold, no avalanche events at site HBS would be recorded. Dubé et al. (2004) calculated an avalanche activity index of 9% for the year 1996 in stand RC, although the treed area devastated was over 50 m². Thus, it is not surprising that historical and tree-ring records of avalanches may not totally correspond (Luckman and Frazer 2001; Butler and Sawyer 2008) for several reasons: (1) the quality and reliability of surveys vary from site to site; (2) a significant change in avalanche survey may have occurred over time and; (3) local factors (slope aspect or gradient) may be responsible for differences in avalanche occurrences in two adjacent sites. Butler and Malanson (1985) indicated that knowledge of site-specific geomorphic conditions helps choosing an acceptable threshold value.

A 10% threshold value appeared appropriate for the avalanche paths studied in the northern Gaspé Peninsula (Larocque et al. 2001; Boucher et al. 2003; Dubé et al. 2004; Germain et al. 2005, 2009). Figure 5 shows that the relative number (%) of recorded avalanche years for variable threshold values follows an exponential distribution ($R^2 = 0.96$; $p < 0.0001$). Using threshold values of $\leq 5\%$, 10% and 20%,

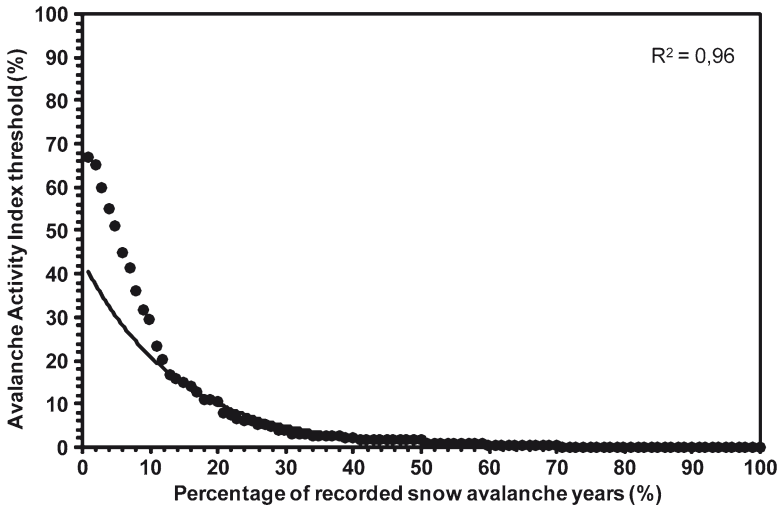


Fig. 5 Percentage of recorded avalanche years for different threshold values. The relative number of recorded avalanche years is the mean number of avalanche years for a given threshold value divided by the length of the chronology at each avalanche path

a total of 50% 20% and 10% of years were identified as avalanche years. A threshold of $\leq 5\%$ may include several small avalanches, and a threshold of $\geq 20\%$ may only include extreme events that cause extensive damage. The exponential distribution (Fig. 5) clearly justifies a 10% threshold, which likely corresponds to high-magnitude snow avalanches, thus excluding small events because the sampling covered the present run-out zone and its immediate forested peripheral in order to minimize the effect of the sampling design.

At the regional scale, Dubé et al. (2004) and Germain et al. (2009) used a 10% threshold value. However, for the regional chronology in alpine–subalpine highlands, this threshold was established by using a robust statistical method rather than subjectively. Indeed, Germain et al. (2009) established this value from a binary step-wise regression model which identified the minimum possible value for avalanche year identification. Avalanche years were characterized by a regional avalanche activity index statistically different from those calculated for non-avalanche years. The regional avalanche activity index takes into account the number of paths that could potentially record an avalanche for a given year, with a sample size ≥ 10 trees.

5.3 Risk Assessment: The Contribution of Dendrogeomorphology

Several recent papers suggest that climate change is likely to cause shifts in the magnitude and frequency of natural hazards (Jomelli et al. 2004; Germain et al. 2009), increasing the exposure of populations to severe disasters, particularly in

mountain environments. Snow avalanches should figure among the most worrying processes because of their great destruction capacity (Gürer et al. 1994; Keiler 2004). In this respect, the tragedies that occurred recently in Europe and the Canadian Cordillera (Jarry and Sivardière 2000; Campbell et al. 2007) raise the question of the accuracy of the present avalanche zoning procedures given the possible impacts of climate change. The long-term reconstruction of diachronous events still represents great interest for risk determination and mapping (Salm 1997). Indeed, the return interval of high-magnitude avalanches for a given run-out distance is still, more than ever, an essential part in land-use planning (McClung 2000).

Because the snow avalanche regime may have been altered by defence structures, forecasting and explosive control and by changes in land use during the last century (Latenser and Schneebeli 2002), historical records may provide a better identification of past events but can hardly be used for precise zoning. Conversely, dendrogeomorphic methods may help characterizing the relative degree of hazard in alpine and subalpine environments where historical records are lacking.

A tree-ring-based avalanche record allows estimation of return intervals and annual probabilities of high-magnitude avalanches at both local and regional scales. However, land managers and engineers show little interest in tree-ring data despite of their usefulness for establishing spatiotemporal variations of high-magnitude events and calculation of run-out distance. Based on extreme events, i.e., ≥ 50 year return interval, run-out distances are usually evaluated using physical or statistical models that need to be calibrated with historical and/or field data. Statistical run-out models known as alpha-beta (Lied and Bakkehoi 1980; McClung and Lied 1987) or runout-ratio models (McClung et al. 1989; McClung and Mears 1991) are easier to use because they are based on topographic parameters. Dendrogeomorphic methods may be very useful for the calibration of such models, but surprisingly very little attention has been paid so far to tree-ring-based avalanche records. Knowledge of avalanche frequencies at the head of run-out zones would allow theoretical estimation of effective return intervals as a function of position along a given slope (McClung 2000). Tree-ring methods thus appear as a practical tool for zoning applications when used in conjunction with run-out models.

6 Conclusion

The important points made in our long-term research program in snow avalanches in the northern Gaspé Peninsula can be stated as follows: (i) the dendrogeomorphic methods provide valuable information on the frequencies (return intervals and annual probabilities) of past snow avalanches; (ii) impact scars and tilted trees with reaction wood are the most reliable evidence of past avalanche events; (iii) the probability to extend avalanche chronologies was high with a sample size of 25–30 trees, but increased only slightly with a sample size >40 ; (iv) a 10% threshold value was appropriate for high-magnitude avalanche identification; and (v) the threshold value can be established using a robust statistical method rather than subjectively.

However, in spite its utility in providing data on frequency-magnitude of geomorphic processes, the accuracy of this methodology has yet to be examined, particularly in regard to distinguishing the effects of other processes, i.e., snow creep, soil creep, and wind that may contribute to noticeable impacts on the tree-rings. In this respect, the use of a statistical technique to establish a threshold value should allow us to go one step further in spatiotemporal modeling. Finally, the scarcity of investigations dealing with spatial mapping (GIS) of avalanche return periods and with tree-ring sequences and icefall activity and slushflows are promising research directions, testifying that this approach is still at the developmental stage.

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