Nat Hazards (2017) 89:201–232
DOI 10.1007/s11069-017-2959-3

ORIGINAL PAPER

Logistic models as a forecasting tool for snow avalanches in a cold maritime climate: northern Gaspésie, Québec, Canada

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Received: 28 February 2017 / Accepted: 4 June 2017 / Published online: 15 June 2017

Abstract Snow avalanches are a major natural hazard for road users and infrastructure in northern Gaspésie. Over the past 11 years, the occurrence of nearly 500 snow avalanches on the two major roads servicing the area was reported. No management program is currently operational. In this study, we analyze the weather patterns promoting snow avalanche initiation and use logistic regression (LR) to calculate the probability of avalanche occurrence on a daily basis. We then test the best LR models over the 2012–2013 season in an operational forecasting perspective: Each day, the probability of occurrence (0–100%) determined by the model was classified into five classes avalanche danger scale. Our results show that avalanche occurrence along the coast is best predicted by 2 days of accrued snowfall [in water equivalent (WE)], daily rainfall, and wind speed. In the valley, the most significant predictive variables are 3 days of accrued snowfall (WE), daily rainfall, and the preceding 2 days of thermal amplitude. The large scree slopes located along the coast and exposed to strong winds tend to be more reactive to direct snow accumulation than the inner-valley slopes. Therefore, the probability of avalanche occurrence increases rapidly during a snowfall. The slopes located in the valley are less responsive to snow loading. The LR models developed prove to be an efficient tool to forecast days with high levels of snow avalanche activity. Finally, we discuss how road maintenance managers can use this forecasting tool to improve decision making and risk rendering on a daily basis.

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Keywords Road · Highway · Avalanche forecast · Statistical analysis · Logistic regression

1 Introduction

In northern Gaspésie (eastern Canada), the road is bounded by a series of steep slopes and the St. Lawrence Estuary. Each winter, an important number of snow avalanches presenting a traffic hazard are reported by the Quebec Ministry of Transport (MTQ) (Fortin et al. 2011; Hétu 2007; MTQ 2005). Most are reported on the national routes 132 and 198, two major transportation corridors linking the eastern part of the Gaspésie peninsula with the road network of western Quebec. According to McClung (1999), the probability of an avalanche hitting a car directly is low. However, even if snow avalanches do not necessarily represent a direct hazard to drivers, they do have a direct socioeconomic impact when major public transportation corridors are blocked by snow avalanche deposits (e.g., Germain et al. 2010; Graveline and Germain 2016; Jamieson and Stethem 2002; Stethem et al. 2003). In northern Gaspésie, between 2000 and 2014, 11 road accidents caused by avalanches have been officially reported by the MTQ, but more minor accidents or cars stuck in snow avalanche deposits are also known to have been observed but not reported (Gasse, personal communication 2013). Furthermore, since the beginning of the twentieth century, road accidents caused by avalanches in this area have killed three people (Fortin et al. 2011; Hétu 2007; Hétu et al. 2008). Before 2016, the MTQ used avalanche bulletin produced two to three times per week by Avalanche Québec for the Chic-Choc mountain range located in the middle of the Gaspésie peninsula. No avalanche forecaster is specifically dedicated to avalanche work along the coast, where weather and snow conditions differ from those of the interior mountain range (Fortin and Hétu 2009, 2013; Fortin et al. 2011; Gagnon 1970).

Avalanche triggering mechanisms are complex and are controlled predominantly by the relationships between slope aspect, topography, weather conditions, and snow structure and metamorphism (e.g., Ancey 2006; Germain et al. 2009; McClung and Schaerer 2006). Mapping avalanche slopes and hazardous road sections is a priority for improving avalanche risk management. In Gaspésie, avalanche slopes and couloirs have been mapped at various scales (Germain 2006; Girard and Hétu 1994; MTQ 2005; Royer and Lemieux 2006; Veillette and Cloutier 1993). However, few studies have linked avalanche activity with climate variables in the area. Tree-ring reconstructions of past snow avalanches show that the long-term frequency of large avalanche activity is high in the area and is well correlated with years characterized by higher than average solid precipitation (Boucher et al. 2003; Dubé et al. 2004; Germain et al. 2005; Martin and Germain 2016). Some more specific weather scenarios (i.e., snowstorm frequency, rain events, facet-crust development, sequences of freezing rain and strong winds, early season weak layers of faceted crystals, and depth hoar) have been proposed by Germain et al. (2009), but remain speculative because of the spatiotemporal resolution of tree-ring analysis. Hétu (2007) and Fortin et al. (2011) investigated the weather conditions prior to snow avalanche occurrence along northern Gaspésie roads. They analyzed 19 avalanches reported by the MTQ between 1987 and 1993, and 141 avalanches distributed over 22 avalanche days spanning three winters (2004–2006), respectively. From these previous works, it was found that snow avalanche occurrence along northern Gaspésie roads depends mainly on the amount of snow accumulated the day of the event or over the 2 days preceding the event. These studies also showed that some avalanches are triggered during rain-on-snow events or when air temperature rises significantly above 0 °C (i.e., wet snow avalanches). Similar kinds of events have been reported in Iceland (Björnsson 1980), New Zealand (Conway 2004; Conway and Raymond 1993; Hendrikx et al. 2005), Montana (Peitzsch et al. 2012), and Alaska (Hendrikx et al. 2014). The collapse of frozen waterfalls or rockwall icings can also trigger snow avalanches (Gauthier et al. 2012, 2013a, 2015b; Graveline and Germain 2016; Hétu 2007).

Establishing strong relationships between weather conditions and avalanche days is one of the first steps toward efficient avalanche forecasting (Ancey 2006; Castebrunet et al. 2012; Durand et al. 1999; Germain 2016; Jomelli et al. 2007; Poggi and Plas 1969; Williams 1998). In this respect, a wide variety of statistical approaches have been used to explain and predict avalanche occurrence (e.g., Bois et al. 1975; Buser 1983; Hendrikx et al. 2014; Perla 1970). For example, classification and regression trees can be used to predict avalanche days following a series of criteria or triggering thresholds (Davis et al. 1999; Hendrikx et al. 2005, 2014; Peitzsch et al. 2012). Logistic regression (LR) has been used to efficiently establish relationships between weather variables and the probability of major avalanche years (Hebertson and Jenkins 2003; Jomelli et al. 2007), but is more rarely used on a daily basis or as a forecasting tool (Jomelli et al. 2007). However, the output, given as a probability of occurrence ranging from 0 to 100%, can easily be used on a day-by-day basis by avalanche forecasters to support more traditional forecasting methods based on snow profile/stability and weather analysis. The underlying challenge in the development of such forecasting models is the lack of reliable data with which to develop them. In northern Gaspésie, although some important critical weather conditions triggering snow avalanches have been proposed, no previous work has statistically linked avalanche activity with weather variables—with the exception of a discriminant analysis performed by Fortin et al. (2011)—mainly because of the lack of avalanche surveys and the scarcity of weather stations providing long-term records (Germain et al. 2010). However, the MTQ database on avalanche activity along the roads of northern Gaspésie now contains 485 events reported over nine avalanche seasons. A sufficient number of events are therefore available to produce frequency probability models based on LR. The current research has three objectives: (1) to analyze the weather conditions before and during some of the most hazardous avalanches that have occurred in recent years; (2) to identify and explain the meteorological variables responsible for avalanche activity on the roadway on a regional and local scale using LR; and (3) to develop forecasting LR models and test their ability to relate snow avalanche occurrence with specific weather patterns. The idea was to develop a simple and complementary tool to assist avalanche forecasters with the analysis of weather data in an operational avalanche forecasting program.

2 Study area

The study area is located on the north shore of the Gaspé Peninsula in eastern Canada (Fig. 1). It covers 70 km of national route 132, between Tourelle and Manche d'Épée, and the first 6 km of national route 198, south of L'Anse-Pleureuse. The annual average daily traffic (AADT) varies from 2000 to 5000 vehicles at the junction of routes 132 and 198 (MTQ 2004). Additionally, between 200 and 500 heavy load trucks, including wind turbine transportation, use these roads every day.

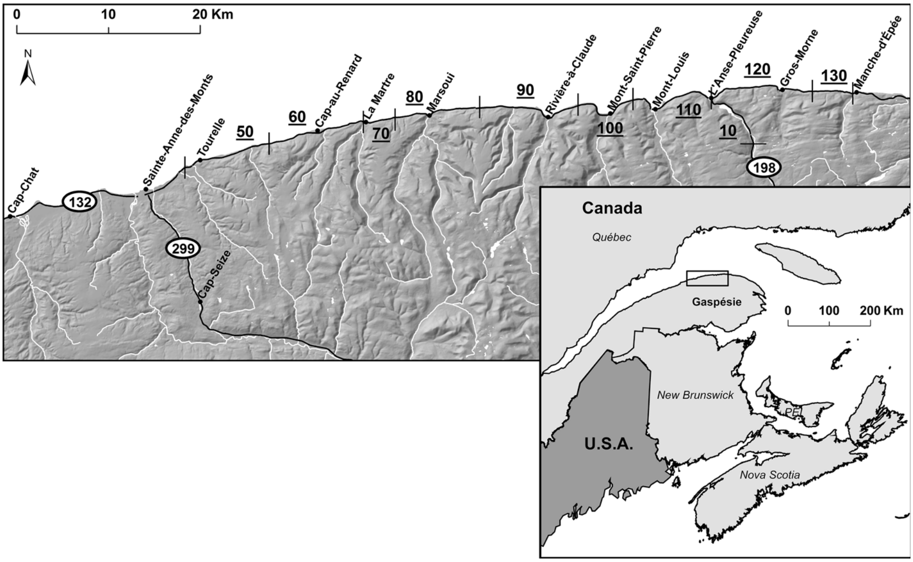

Fig. 1 Study area and the Quebec Ministry of Transport (MTQ) road sections

In many places, the road is squeezed between the St. Lawrence Estuary (i.e., route 132) or a lake (i.e., route 198) and the short (between 50 and 500 m) and steep slopes (>30°) of the Gaspesian plateau (300–450 m high) (Fig. 2) (Hétu and Gray 1985). All slopes face north (0° ± 45°) along route 132 (Fig. 1). In the valley of L'Anse-Pleureuse, the slope threatening route 198 faces southwest. According to Hétu (2007) and Fortin et al. (2011), avalanche-prone slopes can be classified into two categories in northern Gaspésie: (1) large scree slopes and (2) narrow corridors surrounded by forest. Nearly half the road length (7.3 km out of 16 km) between L'Anse-Pleureuse and Manche d'Épée runs directly beneath large scree slopes (75–1200 m wide), which are highly exposed to the dominant western and low-pressure system northeastern winds (Hétu and Vandelac 1989). The length of the slope varies from 55 to 130 m, and the slope angle ranges from 30° at the bottom to 40°–45° near the escarpments (Fig. 2a). East and west of Mont-Saint-Pierre, two large scree slopes (800 m wide each) with similar morphologies are also prone to avalanches (Fig. 2b, c). Along the lake, route 198 runs along a 2-km-long semi-vegetated scree slope (Fig. 2d). Some sections of this slope have been oversteepened to accommodate road construction, increasing instability. This slope, located inside the valley, is less exposed to wind deflation (erosion and transport) than coastal slopes. West of Rivière-à-Claude, most avalanche-prone slopes are narrow corridors (<30 m), ranging from 30 to 280 m long, with slope angles of 30°–60°. Some are old shallow landslide scarps (Lemus-Lauzon 2009).

Ice accumulation on escarpments at the tops of many corridors or scree slopes is frequently observed (Gauthier 2013; Gauthier et al. 2013b, 2015a, b). The collapse of these ice structures, mainly in the spring, sometimes triggers snow avalanches (Fortin et al. 2011; Gauthier et al. 2012; Graveline and Germain 2016; Hétu 2007). The presence of protective infrastructure, essentially ditches and small retaining walls, is not sufficient to stop snow avalanches. These infrastructures fill rapidly with snow, and avalanches can easily reach the road in many places.

Fig. 2 Avalanche of April 14, 2011 (photograph taken on April 15, 2011), route 132, section 120 (**a**); avalanches of February 9, 2010 (photograph taken on February 27, 2010), route 132, section 100, east of Mont-Saint-Pierre (**b**); avalanche of April 4, 2009, route 132, section 100, west of Mont-Saint-Pierre (**c**); avalanche of February 9, 2010, route 198, section 10 (**d**); avalanche of December 30, 2005, route 132, section 130 (**e**); avalanche of March 3, 2013, route 132, section 100, east of Mont-Saint-Pierre (**f**)

The climate of the region is cold temperate with a strong maritime influence. The average daily mean, minimum, and maximum temperatures in January are −11.6, −15.8, and −7.4 °C, respectively (Environment Canada 1981–2010; Gagnon 1970). The maritime influence of the Gulf of St. Lawrence results in an average annual rainfall of nearly 1000 mm spread evenly throughout the year. Thirty-five percent of this precipitation falls as snow from mid-November to late April (Fortin et al. 2011). In winter, cold arctic air masses (−30 °C) can remain stagnant for many days, while warm and wet air from the Atlantic can bring occasional rainy or thaw periods (Fortin and Hétu 2013). The escarpments and the deeply dissected terrain occasionally promote highly localized orographic precipitation, including heavy snow storms (>30 cm/h according to Fortin and Hétu 2009; Fortin and Hétu 2013). Along the coast, slopes are strongly affected by wind, with only 14% of days calm per year, 78% of days in the winter with winds exceeding 30 km/h (December through May), and wind speed frequently exceeding 50 km/h (Environment Canada 1981–2010; Gagnon 1970; Hétu 1992; Hétu and Vandelac 1989).

3 Methods

3.1 Avalanche database

The database used in this study is part of a larger slope movement inventory program started in 1987 by the MTQ Service Centre of Sainte-Anne-des-Monts. Since the initiation of this program, a patrol has circulated year-round and 24 h a day on routes 132 and 198 and has reported rock falls, landslides, ice-block falls, and snow avalanches. Patrollers report the hour of each intervention (i.e., clearing snow, rock, or ice debris from the road) to the Service Centre after their day or night shift. Except for few cases (<5%) where avalanche deposit has been observed in roadside ditches and reported in the database, all others are avalanches that were large enough (the exact size is not recorded) to cover the shoulder or the entire roadway. Since 2000, interventions are recorded in a computerized database. Unfortunately, the inventory data were not recorded every year. During the winters of 2000–2001, 2001–2002, 2002–2003, 2006–2007, and 2007–2008, the data were not recorded. In 2003–2004 and 2004–2005, data acquisition and registration began only in February. Seven avalanche seasons with complete and reliable data (2005–2006, 2008–2009, 2009–2010, 2010–2011, 2011–2012, 2012–2013, and 2013–2014) are available. During these winters (1607 days), and including 2003–2004 and 2004–2005, a total of 485 snow avalanches have been reported over 85 avalanche days.

The MTQ subdivided routes 132 and 198 into 10 distinct road sections (10, and 50–130 in intervals of 10) (Fig. 1). MTQ interventions to clear snow deposits from the roads are reported according to these road sections.

3.2 Meteorological data

The Environment Canada weather station in Cap-Chat (Fig. 1) is one of the closest and most reliable weather stations in the area covering the whole study period. It is located along the coast a few kilometers east of Cap-Chat. Even if some orogeny effect increases local precipitation in certain valleys, particularly in the Mont-Saint-Pierre and L'Anse-Pleureuse valleys (Fortin et al. 2011), the data remain generally representative of the climate in northern Gaspésie, especially along the coast. The weather station records daily precipitation in water equivalent (WE), the daily mean (tmean), maximum (tmax), and minimum (tmin) air temperatures, and wind speed (windsp) and direction (winddir). Meaningful variables for snow avalanche analysis were calculated from these data to develop the LR model (see Table 1 for a complete list of the variables tested to build the model): Liquid ($r1$) and solid ($s1$) precipitations were determined from daily precipitation based on when tmean was higher or lower than 0 °C, respectively; 2–7 days of cumulative antecedent rain ($r2$, $r3$, …, $r7$) and snow ($s2$, $s3$, …, $s7$) precipitation, daily thermal amplitude the day of the event (dtr) and up to 3 days before the event (dtr1, dtr2, and dtr3), thermal amplitude between the day of the event and the previous up to 3 days prior the

Table 1 Description of the meteorological variables used in this study

Ptot:	Daily total precipitation (mm WE)
$r1$:	Daily liquid precipitation (mm WE)
$r2$, $r3$, …, $r7$:	2- to 7-day accrued liquid precipitation (mm WE)
$s1$:	Daily solid precipitation (mm WE)
$s2$, $s3$, …, $s7$:	2- to 7-day accrued solid precipitation (mm WE)
tmean:	Daily mean air temperature (°C)
tmin:	Daily minimum air temperature (°C)
tmax:	Daily maximum air temperature (°C)
dtr:	Daily temperature range (°C)
dtr1, dtr2, dtr3:	Thermal amplitude the day before and up to 3 days before the event (°C)
dtrd1, dtrd2, dtrd3:	Thermal amplitude between the day of the event and the day before and up to 3 days before (°C)
ftc:	Daily freeze–thaw cycle (ftc = 1)
ddp:	Positive degree-days (°C), or the sum of the positive values of tmean calculated for every thaw period
windsp:	Wind speed (km h^{-1})
winddir:	Wind direction (°)

event (dtrd1, dtrd2, and dtrd3), daily freeze–thaw cycle (ftc = 1), which occurs when tmax is higher than 0 °C and tmin is lower than 0 °C, and the positive degree-day (ddp), which is the sum of the positive values of tmean (Gauthier 2013; Gauthier et al. 2012, 2013b, 2015a, b) calculated for every thaw period.

During the winter of 2009–2010, a weather station (Campbell CR10X Data Logger) was in operation at Mont-Saint-Pierre. The station is located 3 km from the coast in the middle of the valley. It provided general meteorological measurements (e.g., air temperature, relative humidity, barometric pressure, and wind speed and direction). It was also equipped with a TE525 tipping-bucket rain gage (±0.254 mm) coupled with a CS705 snowfall conversion adapter and a SR50A sonic ranging sensor to measure snow depth (±1 cm).

3.3 Data analysis: case study

In order to better understand avalanche activity along the coast, the weather data were compared to the occurrence of avalanches as reported by the MTQ. Three major winter avalanche cycles were analyzed: December 2005 to February 2006, February 2010, and March 2013. The first two represent the first type of avalanche cycle, as described by Hétu (2007) and Fortin et al. (2011): Snow avalanches triggered mainly by heavy snow accumulation. The third is a borderline case, where heavy snow and warm temperatures trigger snow avalanches. Finally, we also analyzed the event of spring 2011, where rain-on-snow, warm temperatures, and ice-block falls triggered many avalanches.

3.4 Logistic regression (LR) model

The major challenge when developing statistical avalanche forecasting models arises from the spatial variability of snow accumulation, metamorphism, and the geographical/morphological context. Slope exposure to sun or wind deflation and deposition can result in highly variable snow conditions. In order to minimize these effects within the model, histogram frequency of impacted road sections was produced and analyzed. The probability of snow avalanche occurrence was then calculated for the whole region (regional scale) and for each of the most problematic road sections (local scale): those showing a larger than average proportion of snow avalanches. In each case, the effect of meteorological variables on snow avalanche activity was simulated using binary LR models. This statistical tool is commonly used to explain event occurrence or non-occurrence (dichotomous dependent variable) from a series of variables, in this case the weather data. Such models have frequently been used with success in risk management to explain snow avalanche (e.g., Ancey 2006; Hebertson and Jenkins 2003; Jomelli et al. 2007), ice-block fall (Gauthier 2013; Gauthier et al. 2012, 2015b), or debris flow (e.g., Jomelli et al. 2003, 2004; Sepúlveda and Padilla 2008; Xu et al. 2012) occurrences. The full dataset was used to develop the LR models, except the winter of 2012–2013 on which the models were subsequently tested. All avalanche occurrences were assigned a code of "1," and a code of "0" was assigned to days without avalanche occurrence (see Table 2 for the total number of observations used for each analysis). The probability (P) of snow avalanche occurrence on a given day was calculated from Eq. 1, according to Hosmer and Lemeshow (2000):

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \cdots + \beta_i x_i)}} \tag{1}$$

where β_0 is the intercept (constant) in the model, β_1, β_2, …, β_i are the slope coefficients calculated for the independent variables x_1, x_2, …, x_i. The 31 meteorological variables were systematically tested using a forward (conditional) stepwise analysis in SPSS 20.0. At each step, the most significant variable (highest p value and Wald Z-statistic) was retained. Finally, all significant variables (p value ≤ 0.01) were used to build each LR model. For each case, the best model shows no insignificant variable (p value > 0.05), the highest R^2, and the highest rate of correct prediction (%).

Finally, the best models were tested on the 2012–2013 avalanche season. For each day, the probability of avalanche occurrence (P) was calculated. The output was classified into five classes or level of danger: low (0–20%), moderate (20–40%), considerable (40–60%), high (60–80%), and extreme or very high (80–100%). The performance of the models was assessed by comparing the number of avalanches that occurred in each danger class with the total number of avalanches recorded by the MTQ and the number of avalanche days with the total number of days with this calculated level of danger.

4 Results

4.1 Weather patterns and snow avalanches

4.1.1 Annual frequency

On the roads of northern Gaspésie, an average number of 53.9 snow avalanches are reported each year by the MTQ (Fig. 3a). In fact, this number is highly variable from year to year and ranges from 11 in 2003–2004 to 97 in 2005–2006. The lower than average number of snow avalanches reported in 2003–2004 and 2004–2005 can easily be

Table 2 Statistical parameters of the logistic models

Location	Obs.	Variables	β	SE	Wald Z	p value	Nagelkerke R^2	Correct prediction (%)
Route 132–198 (all road sections)	$N = 1607$	$s1$	0.379	0.021	18.048	<2E−3	0.412	87.2
	NAv = 1200	Intercept	−2.117	0.091	−23.264	<2E−3		
	Av = 407							
Route 132–198 (all road sections)	$N = 1607$	$s2$	0.220	0.012	18.333	<2E−3	0.526	87.0
	NAv = 1200	Intercept	−2.304	0.097	−23.753	<2E−3		
	Av = 407							
Route 132–198 (all road sections)	$N = 1607$	$s3$	0.189	0.010	18.900	<2E−3	0.474	85.5
	NAv = 1200	Intercept	−2.601	0.110	−23.645	<2E−3		
	Av = 407							
Route 132–198 (all road sections)	$N = 1607$	$s2$	0.218	0.012	18.167	<2E−3	0.532	87.8
	NAv = 1200	$r1$	0.089	0.014	6.357	<2E−3		
	Av = 407	windsp	0.018	0.004	4.500	<2E−3		
		Intercept	−3.264	0.192	−17.013	<2E−3		
Route 132 (road sections 50–130)	N = 1545	$s2$	0.212	0.012	17.667	<2E−3	0.544	88.6
	NAv = 1221	$r1$	0.088	0.014	6.286	<2E−3		
	Av = 324	dtr	−0.129	0.026	−4.962	<2E−3		
		windsp	0.027	0.004	6.750	<2E−3		
		Intercept	−3.034	0.286	−10.608	<2E−3		
Route 132 (road section 100)	N = 1349	$s2$	0.216	0.012	18.000	<2E−3	0.529	88.9
	NAv = 1247	$r1$	0.089	0.015	5.933	<2E−3		
	Av = 102	dtr	−0.229	0.030	−7.633	<2E−3		
		Intercept	−1.689	0.186	−9.081	<2E−3		
Route 132 (road sections 120 and 130)	N = 1435	$s2$	0.247	0.014	17.642	<2E−3	0.621	89.3
	NAv = 1262	$r1$	0.101	0.016	6.313	<2E−3		
	Av = 173	windsp	0.032	0.004	8.000	<2E−3		
		dtr	−0.200	0.033	−6.061	<2E−3		

Table 2 continued

Location	Obs.	Variables	β	SE	Wald Z	p value	Nagelkerke R^2	Correct prediction (%)
		Intercept	−3.624	0.351	−10.325	<2E−3		
Route 198 (road section 10)	N = 1355	*s*3	0.141	0.009	15.667	<2E−3	0.597	91.4
	NAv = 1272	*r*2	−0.401	0.136	−2.949	<2E−3		
	Av = 83	dtr1	−0.331	0.044	−7.523	<2E−3		
		Intercept	−1.313	0.249	−5.273	<2E−3		

Av avalanche, *NAv* no avalanche

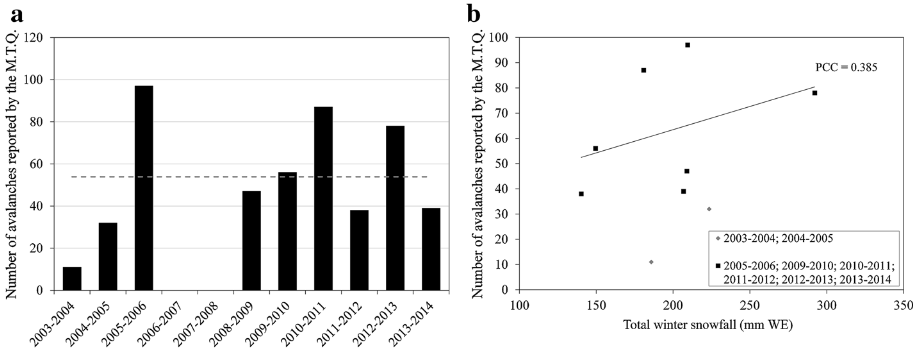

Fig. 3 Annual avalanche frequency (**a**); and correlation between annual avalanche activity and total winter snowfall (**b**)

explained: Avalanches were only recorded in the database as of the middle of the season (from February onward), whereas avalanches were recorded over the full season in other years. Annual avalanche activity shows a positive relationship with the amount of solid precipitation for the given year (Fig. 3b). However, annual frequency does not significantly correlate with total winter precipitation, even when the two half seasons (2003–2004 and 2004–2005) are excluded from analysis.

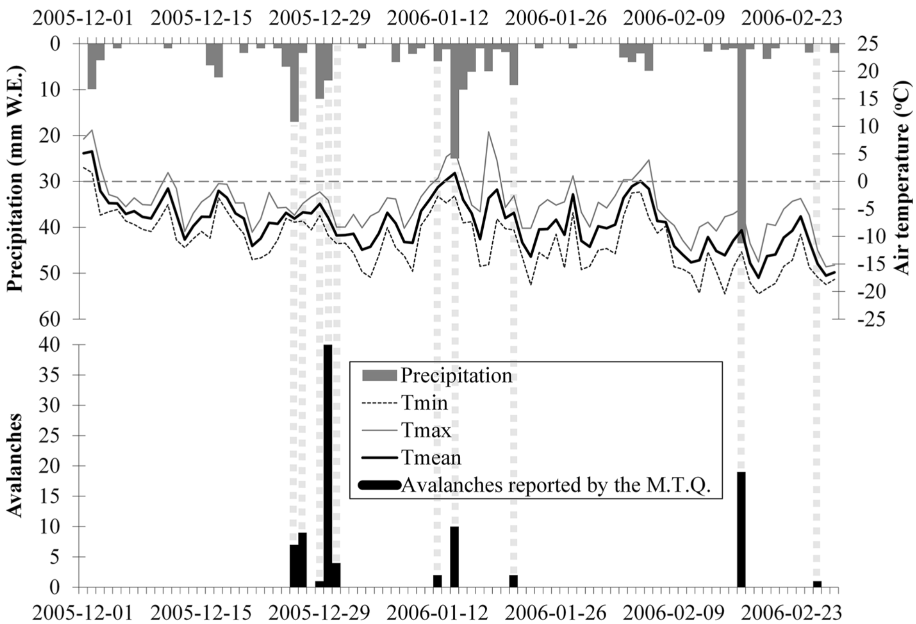

Fig. 4 Daily weather conditions and avalanche activity from December 2005 to February 2006

4.1.2 December 2005 to February 2006

During the winter of 2005–2006, all avalanches occurred during, or the day following, precipitation events (Fig. 4). When mean air temperature is near 0 °C, it can be difficult to determine the state of the precipitation (i.e., snow or rain). In northern Gaspésie, solid precipitation is occasionally followed by a (liquid) rain event within the same day (Fortin et al. 2011; Hétu and Vandelac 1989). In most cases, however, when the maximum daily temperature remains below 0 °C, we can safely assume that precipitation falls only as snow during that day.

The avalanche cycle of December 2005 (61 avalanches) occurred during a snowstorm which resulted in an accumulation of 44 mm WE in 6 days. The air temperature remained below 0 °C throughout the whole period. Most of the avalanches were reported to have occurred at the end of the storm, on December 30 (40 avalanches) (Fig. 4). In some locations, avalanches left deep snow deposits on the road, disrupting traffic for many hours (B. Hétu, personal observation). Only one road accident was officially reported during this period, but many cars got stuck in the snow avalanche deposits (Fig. 2e). One-third of the avalanches were reported to have resulted in deposits on road section 10 (route 198). All the other avalanches resulted in deposits on route 132, mostly on road sections 100 (13 avalanches), 120 (11 avalanches), and 130 (13 avalanches). On January 14, 10 avalanches were reported during a 25-mm WE precipitation event (Fig. 4). During this event, air temperature increased to above 5 °C. Heavy snow or rain-on-snow might have been the triggering factor of these avalanches. Eight of these were reported on road section 130. Finally, on February 17, an intense snowstorm of 43.5 mm WE in only 1 day triggered 19 avalanches (Fig. 4). Once again, most of the avalanche deposits were reported on road sections 10 (5 avalanches) and 130 (10 avalanches). In both cases, avalanches seemed to correlate with the amount of solid precipitation accrued the day of the event or occurring within the few days leading up to the event.

4.1.3 February 7 to 9, 2010

The avalanche cycle of February 8 and 9, 2010, caused the greatest concern to the MTQ in recent years. According to the Environment Canada weather station in Cap-Chat, 35 mm WE of snow fell between February 7 and 9 (Fig. 5a). However, our weather station in Mont-Saint-Pierre valley recorded 57.7 mm WE of solid precipitation (or 123.3 cm of snow) falling in 48 h, from February 7 to 9 at midnight (Fig. 5b). Forty-six avalanches were reported during the night of February 8 to 9 on all road sections (Fig. 5a). On road section 10 (road 198), five major avalanches (size 3 according to the Canadian Snow Avalanche Size Classification System, in McClung and Schaerer 2006) were triggered just after midnight on February 9, blocking the road for many hours (incident report by Charles-A. Gasse, MTQ). One resulted in a wet snow avalanche deposit ranging from two to four meters high over more than half a kilometer (Fig. 2d). This (route 198) is the only road connecting the village of the interior peninsula (Murdochville) to the coastal road (route 132) and is also frequently used for wind turbine transport.

4.1.4 February and March 2013

Fifteen avalanches were reported between February 21 and 23, following a snowstorm of 43 mm WE over 48 h, with antecedent solid precipitation of 20 mm WE on February 17

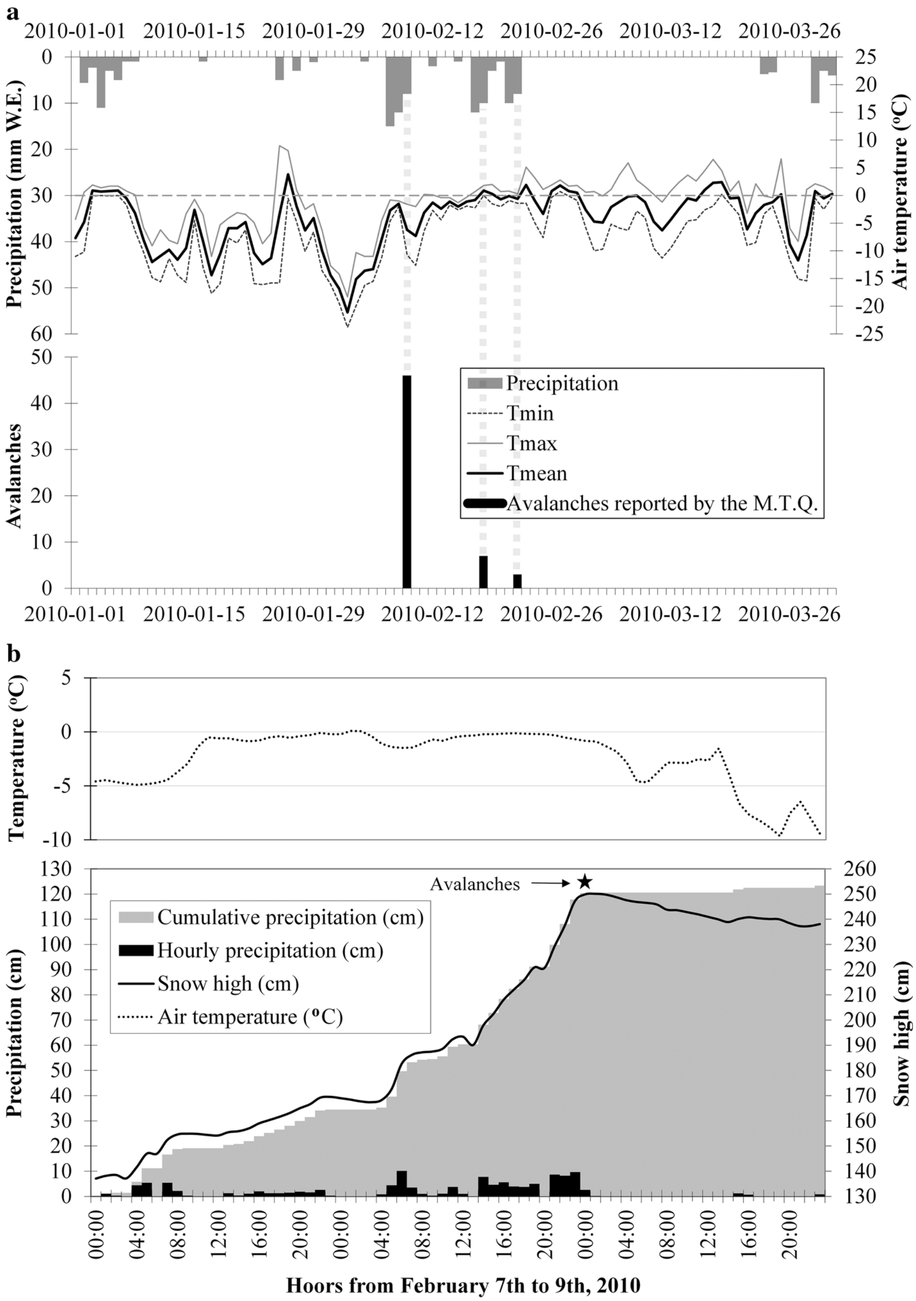

Fig. 5 Daily weather conditions and avalanche activity from January to March 2010 (**a**); hourly weather conditions between February 7 and 9, 2010 (**b**)

and 18 (Fig. 6). No accidents were reported during this period, and avalanches impacted road sections 100, 120, 130 (route 132), and 10 (route 198). Seven days later, on March 2 and 3, a major low-pressure system brought 87.1 mm WE of wet snow and liquid

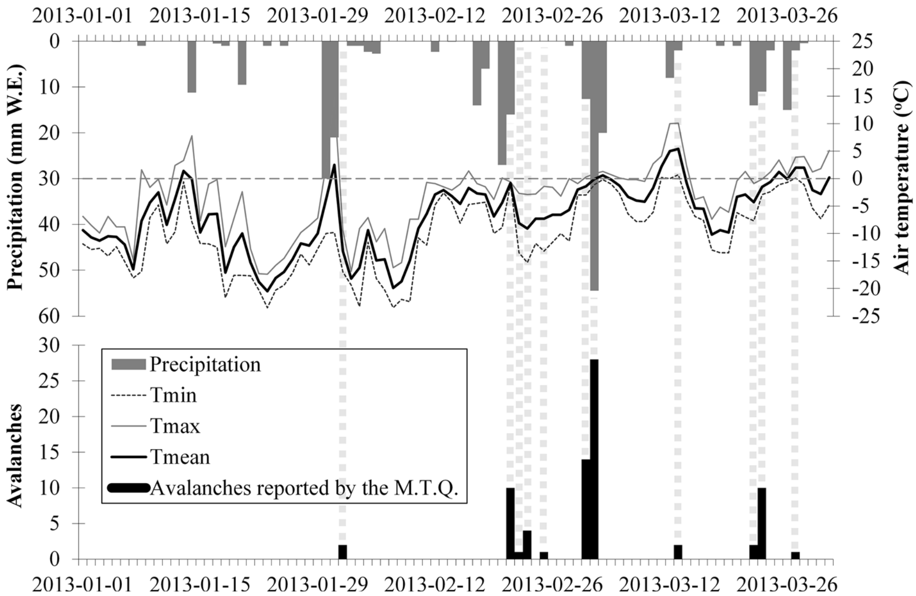

Fig. 6 Daily weather conditions and avalanche activity from January to March 2013

precipitation in northern Gaspésie. According to D. Boucher from Avalanche Québec, more than 100 cm of snow fell during this period. Heavy, wet snowfall, combined with warm air temperatures, triggered 42 wet snow avalanches (Fig. 6). East of Mont-Saint-Pierre (road section 100), avalanche deposits were five meters deep, reaching the overhead power lines (Fig. 2f).

4.1.5 Spring and rain-on-snow avalanches of 2011

According to Fortin et al. (2011), Hétu (2007), and Germain et al. (2009), prolonged thaw and rain-on-snow events are the second most important triggering factors of snow avalanches at higher elevations in Gaspésie. In 2011, many avalanches occurred during rainy thaws (Fig. 7). This is especially obvious in late April and early May, when even overnight air temperature remained above 0 °C. However, no major avalanche cycle with a large number of avalanches was reported during this period. The frequency of wet snow avalanches seems to be more correlated with rain events than with warm days (Fig. 7). During these rainy, warm periods, avalanches tend to slide directly on the ground, triggering small- to medium-sized full-depth (or ground) slab avalanches (Fig. 2a, c).

In the spring, ice-block falls can also trigger snow avalanches (Fortin et al. 2011; Gauthier et al. 2012; Graveline 2012; Hétu 2007). The melting and ensuing collapse of rockwall icings (and frozen waterfalls) can be predicted by calculating the positive or melting degree-days (e.g., Gauthier et al. 2015a, b). Other factors, such as large air temperature fluctuations (or freeze–thaw cycles), which favor crack opening, can trigger ice-blocks falls (e.g., Gauthier et al. 2012; Weiss et al. 2011). Variables triggering ice-blocks falls should also be taken into account in the daily snow avalanche LR model.

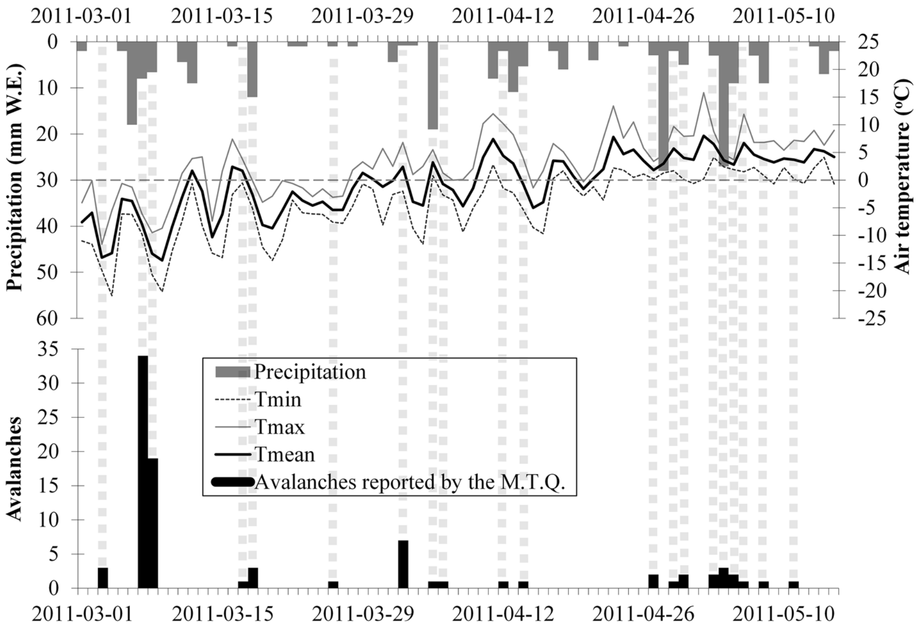

Fig. 7 Daily weather conditions and avalanche activity from March 1 to May 15, 2011

4.2 Spatial distribution of snow avalanches

The spatial distribution of avalanches in northern Gaspésie is mainly concentrated within four road sections (10, 100, 120, and 130) (Fig. 8). The few avalanches occurring on road section 60 to 90 are from narrow couloirs located on 30°–60° vegetated slopes. Slope

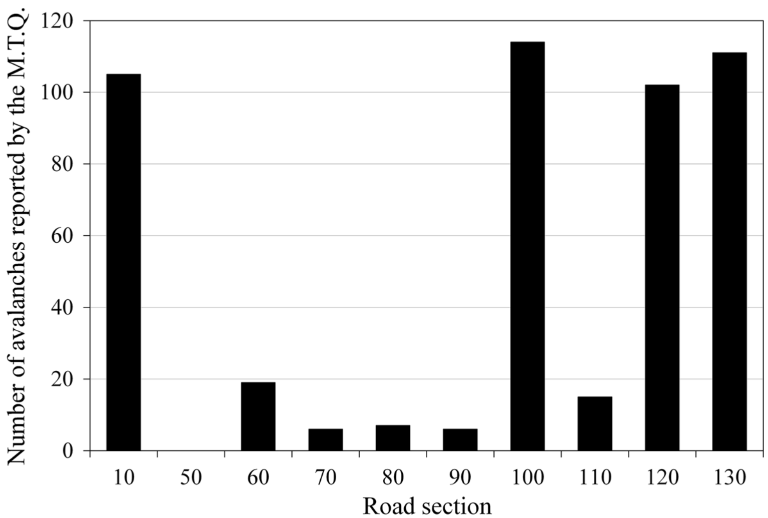

Fig. 8 Total number of avalanches reported by road section

dynamics of some of these couloirs are controlled by the seasonal collapse of rockwall icings (Gauthier 2013; Gauthier et al. 2013a; Graveline and Germain 2016; Hétu 2007). The others are old shallow landslide scarps (Lemus-Lauzon 2009). Avalanches on road section 110 also occurred on shallow landslide scarps.

Avalanches on road section 100 arise mainly from two wide scree slopes located east and west of the village of Mont-Saint-Pierre (Figs. 1, 2b, c). Together, these represent almost 2 km of highly active slopes prone to avalanches (26% of the total length of road section 100). Slopes east of the village are connected to six 300–400 m chutes (Fig. 2b). Snow can accumulate in these steep (40°–55°) and narrow (5–20 m) couloirs, and avalanches generally originate from them. However, these slopes are also exposed to wind deflation, resulting in the formation of a hard wind crust, and in extreme cases leaving the slopes free of snow (Hétu 1992, 1995; Hétu and Vandelac 1989). The active scree slopes west of Mont-Saint-Pierre are more protected from wind deflation, since they are not exposed to the dominant winds. However, they are overlooked by a 60–100-m-high cliff, where many rockwall icings form during the winter (Fig. 2c). Some snow avalanches can be triggered by ice-block falls arising from these ice structures.

Together, road sections 120 and 130 represent the most active avalanche-prone slopes in northern Gaspésie (Fig. 8). The wide (75–1200 m) and steep (35°–45°) scree slopes and many shallow landslide scarps cover 45% (7.2 km) of the total length of these two road sections (Fig. 2a). Slopes here are more exposed to wind deflation than any other road sections in the area (Hétu 1995; Hétu and Vandelac 1989). During blizzards, winds can reach 100 km/h. The icy and smooth scree slopes that remain following these events are perfect slide surfaces for the next snowfall.

1700 meters of road section 10 (route 198) are exposed to 100- to 300-m-long and 35°–40° semi-vegetated slopes (Figs. 1, 2d). Unlike all the slopes facing north and exposed to dominant winds along route 132, this slope faces southwest and is well protected from strong wind deflation. Its location in the valley of L'Anse-Pleureuse is more prone to snow deposition. Snow accumulation and the development of a persistent layer of sun or rain crust are more probable here. Furthermore, this slope has been oversteepened over almost its entire length to permit road construction along the lake. This may explain the high avalanche activity present on this road section (Fig. 8).

4.3 Daily-basis logistic model

Different models were developed for each selected road section. The statistical parameters of the different logistic models are presented in Table 2. All models tested for the whole area (all road sections included) fit well with 1-, 2-, or 3-day accrued solid precipitation ($s1$, $s2$ and $s3$, respectively) (Fig. 9a). However, the best estimate was obtained using $s2$ (i.e., highest resulting R^2). When 10 mm WE of solid precipitation falls in 2 days, the probability of avalanche occurrence is close to 0.45, reaching 0.9 with 20 mm WE of snow. The model shows even stronger prediction when daily liquid precipitation ($r1$) and average wind velocity the day of a given event (windsp) are added. Both rain and wind speed tend to increase the probability of avalanche occurrence (Fig. 10a, b). Adding any other variables to the model does not increase the coefficient of determination (R^2) or rate of correct prediction. With such a model, the probability of avalanche occurrence can reach 0.85 even when no snow is accumulated the day of the event or the day prior to the event (Fig. 9b). Similar results were obtained when road section 10 (route 198) was removed, leaving only road sections 50 to 130, located along the coast (route 132) in the analysis

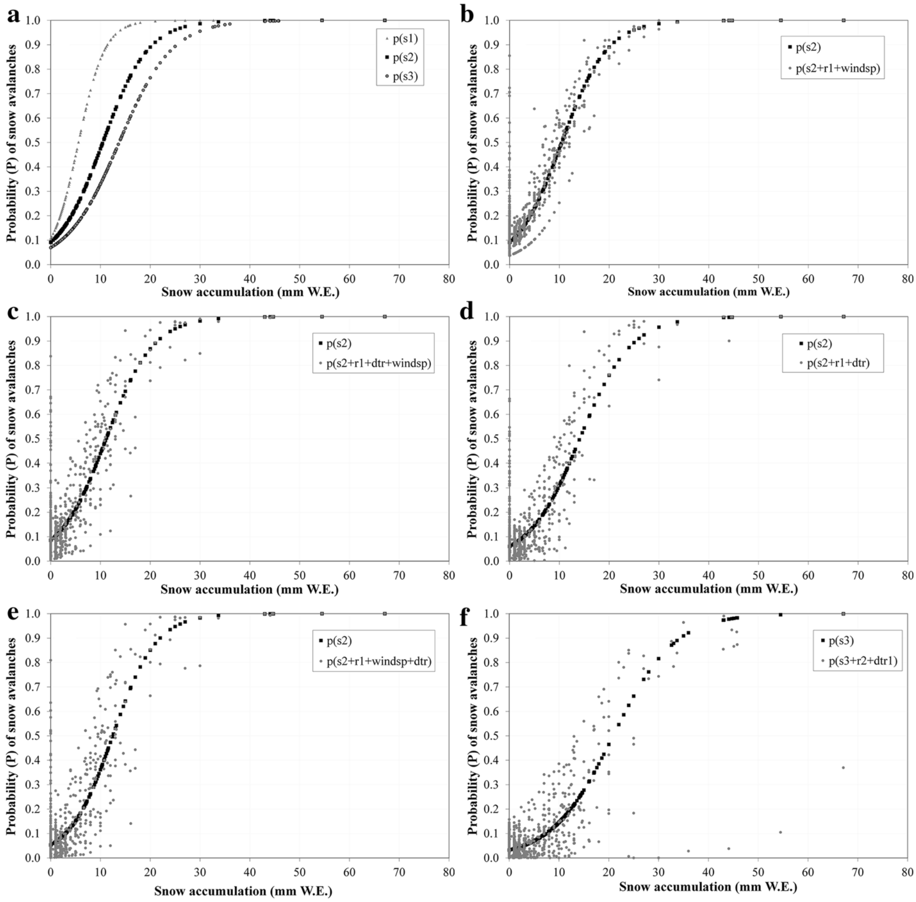

Fig. 9 Probability of avalanches on a daily basis on routes 132 and 198, all road sections (**a**, **b**); on route 132, sections 50–130 (**c**); on route 132, section 100 (**d**); on route 132, sections 120 and 130 (**e**); and on route 198, section 10 (**f**)

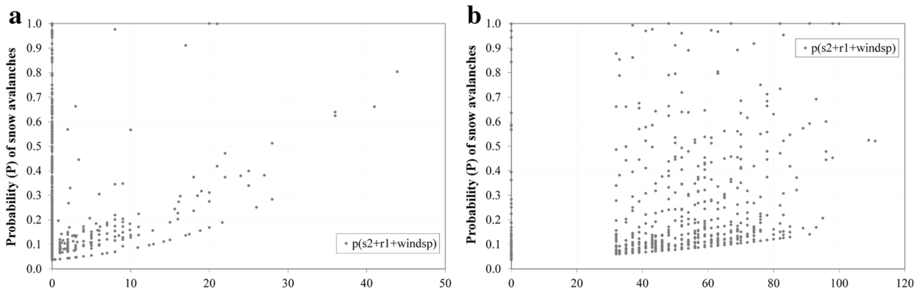

Fig. 10 Daily liquid precipitation (**a**) and daily average wind velocity (**b**) effects on the probability of avalanche occurrence along routes 132 and 198

(Table 2; Fig. 9c). In this case, the daily temperature range (dtr) becomes a significant meteorological parameter and slightly increases the rate of correct prediction.

Considered separately, the best models for road section 100 and 120–130 both include *s*2 and *r*1. Daily thermal amplitude (dtr) proves to be a significant variable in the model for road section 100. For road sections 120 and 130, dtr is also significant, as is the average wind velocity the day of a given event. A probability of avalanche occurrence of 0.5 is reached when snow accumulation exceeds 14 mm WE in 2 days on road section 100 (Fig. 9d), while only 12.5 mm WE of snow in 2 days is needed on road section 120 to 130 to reach the same level of probability (Fig. 9e).

For road section 10 (route 198), three significant meteorological parameters were retained: (1) 3 days of cumulative snowfall (*s*3), (2) 2-day accrued rain (*r*2), and (3) thermal amplitude the day before an event (dtr1). Probability of avalanche occurrence reaches 0.5 when 21 mm WE of snowfalls in 3 days and can increase to 0.99 with the occurrence of *r*2 and if a large thermal amplitude is observed the day before a given event (Fig. 9f).

4.4 Logistic model analysis: training season 2012–2013

The LR models were tested on the 2012–2013 avalanche season (Fig. 11, Appendix Figs. 13, 14, 15, 16, 17, 18 and 19; Tables 3, 4). Each day, the level of danger (i.e., 5 classes) was calculated using the models. On a regional scale, the model $P(s2 + r1 + \text{windsp})$ peaks above 60% (14 days with high and very high level of danger) during the four major avalanche cycles (Fig. 11; Table 4). Seventy-three avalanches (10 avalanche days) were reported during these periods. Of these, 50 avalanches (4 avalanche

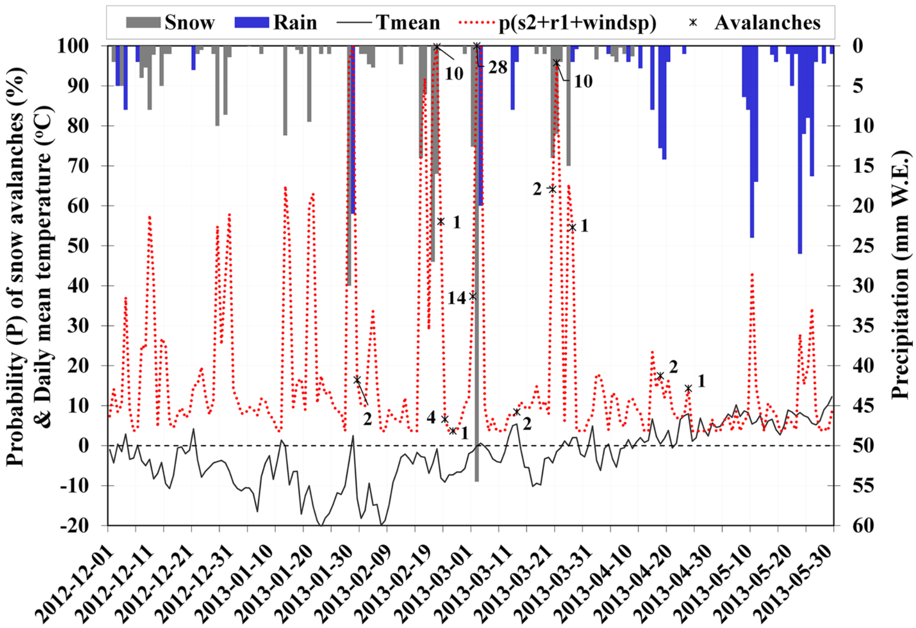

Fig. 11 Logistic model $p(s2 + r1 + \text{windsp})$ used to forecast snow avalanches on routes 132 and 198 (all road sections) in northern Gaspésie during the winter of 2012–2013

Table 3 Winter 2012–2013: Number of avalanches that occurred in this level of danger/total number of avalanches by road sections (%)

Probability (*P*) of snow avalanches using five classes avalanche danger scale	Road 132 and 198 (all road sections)				Road 198 (section 10)	Road 132 (sections 50–130)	Road 132 (section 100)	Road 132 (sections 120–130)
	P (*s*1)	*P* (*s*2)	*P* (*s*3)	*P* (*s*2 + *r*1 + windsp)	*P* (*s*3 + *r*2 + dtr1)	*P* (*s*2 + *r*1 + dtr + windsp)	*P* (*s*2 + *r*1 + dtr + ftc)	*P* (*s*2 + *r*1 + windsp + dtr)
Very high *P* (80–100%)	64/78 (82%)	28/78 (36%)	51/78 (65%)	48/78 (62%)	11/22 (50%)	36/56 (64%)	6/12 (50%)	30/40 (75%)
High *P* (60–80%)	0/78 (0%)	26/78 (33%)	4/78 (5%)	2/78 (3%)	0/22 (0%)	0/56 (0%)	0/12 (0%)	0/40 (0%)
Considerable *P* (40–60%)	0/78 (0%)	10/78 (13%)	17/78 (22%)	2/78 (3%)	5/22 (23%)	2/56 (6%)	0/12 (0%)	2/40 (5%)
Moderate *P* (20–40%)	0/78 (0%)	0/78 (0%)	0/78 (0%)	14/78 (18%)	1/22 (5%)	11/56 (20%)	3/12 (25%)	7/40 (18%)
Low *P* (0–20%)	14/78 (18%)	14/78 (18%)	6/78 (8%)	12/78 (15%)	5/22 (23%)	7/56 (13%)	3/12 (25%)	1/40 (3%)

Table 4 Winter 2012–2013: Number of avalanche days in this level of danger (number of avalanches that occurred in this level of danger)/total number of days with this level of danger (%)

Probability (P) of snow avalanches using five classes avalanche danger scale	Road 132 and 198 (all road sections)				Road 198 (section 10)	Road 132 (sections 50–130)	Road 132 (section 100)	Road 132 (sections 120–130)
	P ($s1$)	P ($s2$)	P ($s3$)	P ($s2 + r1 +$ windsp)	P ($s3 + r2 +$ dtr1)	P ($s2 + r1 +$ dtr + windsp)	P ($s2 + r1 +$ dtr + ftc)	P ($s2 + r1 +$ windsp + dtr)
Very high P (80–100%)	5(64)/12 (42%)	1(28)/3 (33%)	5(51)/11 (46%)	3(48)/8 (38%)	3(11)/4 (75%)	3(36)/9 (33%)	3(6)/4 (75%)	3(30)/7 (43%)
High P (60–80%)	0(0)/2 (0%)	3(26)/5 (60%)	1(4)/5 (20%)	1(2)/6 (17%)	0(0)/4 (0%)	0(0)/3 (0%)	0(0)/3 (0%)	0(0)/5 (0%)
Considerable P (40–60%)	0(0)/3 (0%)	1(10)/4 (25%)	3(17)/8 (38%)	2(2)/10 (20%)	2(5)/4 (50%)	1(2)/10 (10%)	0(0)/2 (0%)	1(2)/6 (17%)
Moderate P (20–40%)	0(0)/8 (0%)	0(0)/5 (0.0%)	0(0)/14 (0%)	1(14)/13 (8%)	1(1)/10 (10%)	1(11)/16 (6%)	1(3)/5 (0%)	1(7)/10 (10%)
Low P (0–20%)	8(14)/157 (5%)	8(14)/162 (5%)	4(6)/144 (3%)	6(12)/145 (4%)	2(5)/160 (1%)	4(7)/144 (3%)	2(3)/168 (2%)	1(1)/154 (1%)

N.B.: 182 days (all road sections: 13 avalanche days/169 non-avalanche days; section 10: 8 avalanche days/174 non-avalanche days; sections 50–130: 9 avalanche days/173 non-avalanche days; section 100: 6 avalanche days/176 non-avalanche days; sections 120–130: 6 avalanche days/176 non-avalanche days)

days) occurred when the model calculated a probability of occurrence above 60%, 9 avalanches (5 avalanche days) occurred within the following two or 3 days when the model dropped to a lower probability level, and 14 avalanches (1 avalanche day) occurred during the first day of the snow storm when the probability of occurrence was still less than 60% (Tables 3, 4). Before the storm of January 30 and 31, the model reacted to snowfall and calculated a probability of occurrence of between 40 and 65% (i.e., considerable and high level of danger). However, no avalanche actually occurred during these periods. To explain these early season nonevents, we developed a triggering threshold based on 2 days of snow accumulation and the total snow accumulation since the beginning of the avalanche season (or December 1) (Fig. 12). During the 9 avalanche seasons used in this study, no avalanches have been reported before total snow accumulation reached 45–50 mm WE. Furthermore, few avalanches were found to occur below a precipitation threshold of 10 mm WE. Most of these events are mid- and late-season rain-on-snow avalanches, or wet snow avalanches initiated during rainy and thaw periods (>0 °C) (Fig. 12).

The one parameter model, $P(s1)$, is highly reactive to snowfall (Appendix Fig. 13), as can be seen in the higher number of days with a high or very high levels of probability (>60%) (Tables 3 and 4). Models $P(s2)$ and $P(s3)$ are less reactive and were able to calculate considerable to very high levels of danger when needed, resulting in less non-avalanche days forecast with a high level of danger (Appendix Figs. 14, 15; Tables 3 and 4). Finally, the models developed specifically for each road section show comparable results to the three parameter regional scale model, $P(s2 + r1 + \text{windsp})$ (Appendix Figs. 16, 17, 18 and 19; Tables 3, 4).

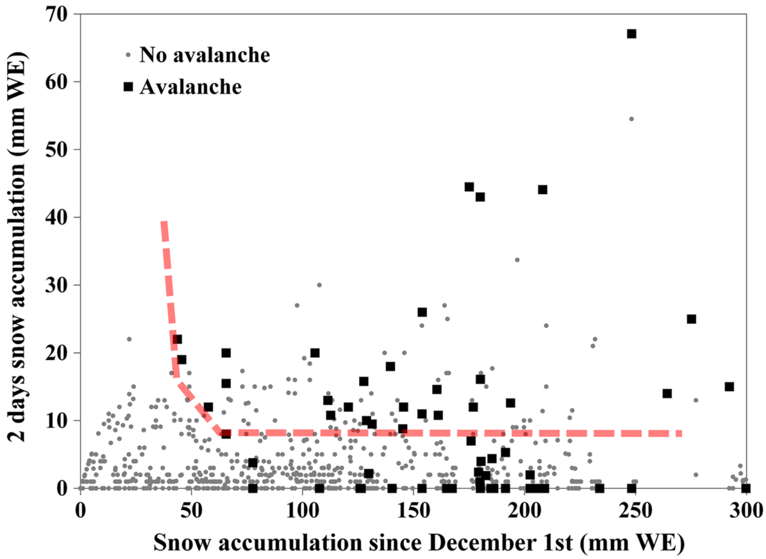

Fig. 12 Relationships between two-day snow accumulation and total snow accumulation since December 1 and number of triggered avalanches

5 Discussion

5.1 Data reliability

The avalanche database analyzed in this study contains 485 events reported over 9 avalanche seasons (1607 days). Logistic regression is usually robust enough to handle unbalanced data since they only affect the estimate of the model intercept. Different techniques can be used to correct the estimate of the model intercept, but they are generally used to explain rare events when one group makes 1% or less in a sample (e.g., King and Zeng 2001). This could have been useful to explain some avalanche occurrences triggered by uncommon weather pattern or other non-weather-related triggering factor. In our case, avalanche occurrences represent 6–25% of the distribution. We choose not to balance the dataset to make sure the output of the model would not be an estimate of the a posteriori probability. Furthermore, the quality of the survey is highly variable and also depends on human observation. Therefore, most of the avalanches reported are those that reach the road. It is likely that many smaller avalanches remained unnoticed. A more thorough survey would bring to light more events correlated with weather data. This may result in a greater significance of the variables tested and increase the reliability of the models.

The weather data used in this study are from a station located 60–80 km away from the most hazardous road sections. Precipitation, controlled by large weather systems but also by local topography, can be highly variable throughout the study area. The snowstorm of February 7–9, 2010, is a good example: The weather station in Cap-Chat recorded 35 mm WE during these 3 days, whereas our weather station in Mont-Saint-Pierre valley recorded 123 cm of snow (or 58 mm WE) on February 7 and 8 alone. Therefore, it seems that the deep valley and steep escarpment bordering the coast strongly affects the precipitation pattern. It is probable that the weather station in Cap-Chat underestimates the amount of snow (or rain) that may be received further east along the coast and in the multiple valleys opening onto the estuary. This does not necessarily invalidate the models, but may change the interpretation of some results, such as providing a lower limit or underestimation of the amount of snow required to trigger avalanches.

5.2 Influence of the meteorological variables on snow avalanche initiation

5.2.1 Regional scale

In large mountain ranges, such as the Alps and the American Rockies, as well as in the smaller ranges of Norway and Scotland, the probability of avalanche occurrence is mainly correlated with solid precipitation, and especially with the 3-day cumulative snowfall preceding a given event (e.g., Ancey 2006; Bakkehoi 1987; Butler 1986; De Quervain and Meister 1986; Jomelli et al. 2007; Mc Clung and Tweedy 1993; Ward 1984). In northern Gaspésie, the probability of a snow avalanche is more strongly correlated with the snowfall accrued the 2 days preceding an event. This supports the avalanche scenarios proposed by Hétu (2007) and Fortin et al. (2011). The large scree slopes along route 132 are highly affected by wind deflation (erosion and transport), leaving the slopes free of snow, or smooth and icy for the next snowfall. The development of a deep snow pack is rare, and the slopes are highly reactive during snowstorms. Therefore, the probability of occurrence increases rapidly during a snowstorm, and even small accumulations (10 mm WE) can trigger an avalanche.

Daily liquid precipitation is the second most important variable increasing the probability of avalanche occurrence in northern Gaspésie. Rain and prolonged thaw periods are well-known avalanche triggers and have been reported in many previous works (Butler 1986; Conway 2004; Conway and Raymond 1993; Germain et al. 2009; Hendrikx et al. 2005; Heywood 1988; McClung and Schaerer, 2006; Peitzsch et al. 2012). According to Perla (1970), even low precipitation rate (0.8–2.5 mm/h) can contribute to snow avalanche initiation. The avalanches of March and April 2011 demonstrated that even a small amount of rain (10–30 mm) can trigger an avalanche (Fig. 7). Those of January 30–31 and March 2–4, 2013, show that rain-on-snow is an especially efficient trigger when concomitant with a snowfall (Fig. 6). This reinforces observations made by Hétu (2007) and Fortin et al. (2011) in northern Gaspésie and by Heywood (1988) in the Alpine Meadows Ski Area (Sierra Nevada, California).

Wind is also recognized as an important snow transport agent and avalanche triggering factor (Germain et al. 2009; Germain et al. 2005; McClung and Schaerer 2006; Meister 1989; Perla 1970). Along the coast of northern Gaspésie, strong winds during snowstorms play a direct role in the avalanche formation by increasing snow accumulation in couloirs and along the forest fringe. But after and before snowstorms, strong dominant western and low-pressure system northeastern winds are leaving the slopes free of snow with a thin wind crust snow layer along the forest fringe (Fortin et al. 2011; Hétu, 2007). Therefore, the significance of wind as a predictive variable cannot be associated with such a scenario. Further study would be needed to better understand wind deflation processes on these slopes between snowstorms.

5.2.2 Local scale (road sections)

The models developed for specific road sections with similar geographical contexts resulted in better coefficients of determination than the regional model. Furthermore, the more significant variables responsible for snow avalanche initiation tend to change with the different models. The models developed for road sections located along the coast (route 132), and especially for road sections 100, 120, and 130, show better prediction with 2-day accrued precipitation (*s*2), rain the day of a given event (*r*1), and wind speed (windsp). This may reflect the greater reactivity of the large scree slopes exposed to wind deflation. Daily temperature range (dtr) was also found to be a significant variable in the model developed for these specific road sections. This reinforces the well-known influence of air temperature, and more specifically of high thermal variation, in the development of a weak layer (e.g., Colbeck and Jamieson, 2001; McClung and Schaerer 2006). Moreover, large thermal amplitude can induce enough mechanical stress to open cracks in rockwall icings and trigger ice-block falls, which is a well-known avalanche trigger along the coast of northern Gaspésie (e.g., Fortin et al. 2011; Gauthier et al. 2015b; Graveline and Germain 2016; Hétu 2007). Consequently, dtr may increase the probability of snow avalanches through ice-block falls.

Because of its location in the valley of L'Anse-Pleureuse, the slope bordering route 198 (road section 10) is less exposed to wind deflation than the slopes along the coast. Moreover, the slope bordering route 198 faces southwest and as such is also more exposed to direct solar radiation. The significant variables of the model in this specific case may reflect the following: (1) The model is less sensitive to direct solid precipitation [3-day accrued solid precipitation (*s*3)], and snow loading over a longer period of time (3 days) is required for avalanche initiation, (2) longer periods of rain (*r*2) are required to trigger an avalanche, and (3) temperature variation (dtr1) in a more persistent snow cover exposed to solar radiation may favor the development of weak layer over sun crust. These assumptions support well-understood snow metamorphism and weak layer development processes (e.g., Colbeck and Jamieson 2001; McClung and Schaerer 2006; Schweizer et al. 2003).

5.3 Logistic models performance

For the 2012–2013 avalanche season, the LR models were tested in an operational avalanche forecasting perspective. The models show interesting forecasting potential, especially with regard to targeting avalanche days with a high level of avalanche activity (many avalanches). These events generally arise in association with mid-winter or late-season heavy snow storms and account for 88% of the avalanches reported by the MTQ since 2004. However, it does not mean that high or very high level of probability automatically comes with more than one avalanche on a given day. But this demonstrates that most avalanches occur during storms. This is in good agreement with the findings of Hétu (2007) and Fortin et al. (2011), who highlight the high reactivity of avalanche initiation to snow accumulation. In this cold maritime climate, it is not unusual for heavy snowfalls to turn into rain or wet snow before the end of the precipitation event (Fortin et al. 2011; Hétu 2007). In the model, wet snowfall may sometimes be interpreted as a rain event. This systematic bias results from the temperature threshold (0 °C) used to discriminate daily snow from rain events. However, adding the daily liquid precipitation (r1) to the model allowed a high level of probability (>60%) to be retained during this particular type of event. After a snowfall, the probability computed by the model decreases rapidly (Fig. 11, Appendix Figs. 13, 14, 15, 16, 17, 18 and 19). This can limit the forecast of avalanches that may occur in the few days following a snowstorm. In all models tested, 2 or 3 days of accrued snowfall tends to be the most significant parameter, followed by the amount of daily liquid precipitation, the daily maximum wind speed, and/or the daily temperature variation. In each model, more weight is given to the first (i.e., most significant) parameter: snowfall (see β in Table 2). This reduces the weight of rain (or any other less significant parameter) in the model, leading to lower levels of probability during isolated rain-on-snow events and fewer avalanches triggered during rainy thaws. The probability stands between 10% for rainy thaws (i.e., low level of danger) and 45% during heavy rain events (i.e., considerable level of danger). Such events account for 8% of the avalanches reported by the MTQ since 2004. Most of these occur in late March or April, at the end of the avalanche season. According to the road maintenance manager, these events are mostly small or very small avalanches ($D1$ or $D2$) and are rarely medium avalanches ($D3$) that can buried a car (Fig. 2a). These events generally occur after many days of thaws and can easily be located where residual snow patches remain. Still, according to the road manager, more rain-on-snow events are reported in the winter (e.g., the avalanche of March 13, 2013), and these events may be more difficult to forecast with the LR models. In the context of climate change, more attention should be paid to these types of avalanches and weather patterns.

In northern Gaspésie, no full-time avalanche management program is currently operational, and the road maintenance manager is not a fully trained operational avalanche forecaster. The forecast comes from avalanche bulletin produced by Avalanche Quebec for the Chic-Choc mountains. The nonprofit organization, dedicated to public avalanche safety, does not have enough resources to carry out regular monitoring of the snow conditions along the coast. The weather and especially the snow conditions in the interior plateau of the peninsula are very different from those observed along the coast (Fortin and Hétu 2009; Fortin and Hétu 2013; Fortin et al. 2011; Gagnon 1970). As such, the LR models developed in this study may provide one of the easiest and most intuitive forecasting tools available. The models can easily be interpreted for day-to-day risk rendering and decision making. It would be easy for the manager to dispatch road patrollers and snowplows, or to proceed to road closure, during the most obvious avalanche cycles with forecasted high and extreme levels of danger. Furthermore, Environment Canada provides up to 7-day weather forecast, with information on temperature, precipitation, and wind speed, and an hourly weather forecast for the next 24 h. Even if there are systematic differences (biases) between actual weather and forecast weather (e.g., Roeger et al. 2003), the data can be used as input into the models to support logistical preparation.

The simplicity of the models does not necessarily guarantee the safe and proper interpretation of the results they produce. A well-trained avalanche forecaster would be needed to ensure the full potential of the method. The model will not replace a complete snowpack analysis, especially between and outside of the most obvious heavy snow storms. For instance, the model reactivity to snowfall can lead to many false alarms at the beginning of the season. An experienced avalanche forecaster would be able to assess and compare the level of danger calculated by the model with their own interpretation. The expertise of a traditional avalanche forecaster would also be needed to locate the most hazardous slopes during snow storms, but also (and especially) outside of these periods. Even if meaningful parameters have emerged in the development of the local-scale models (i.e., for each road section), no significant difference in performance from that of the regional model was found when testing it locally. A greater number of avalanche days may be needed to highlight the benefits of the local models. Adding multiple training season (i.e., events) and traditional forecast to the analysis would also allow more accurate verification probability methods (e.g., Jolliffe and Stephenson 2011). To ensure optimal performance of the method, the LR models should be rerun every year to include data from the most recent season. The models should also subsequently be tested on multiple years, with different winter weather patterns, to ensure their reliability.

6 Conclusions

With almost 500 snow avalanches (85 avalanche days over 1200 non-avalanche days) reported in the past 11 years on the roads of northern Gaspésie, avalanches represent a serious natural hazard for road users and infrastructure. To better manage the associated risk in this region, an avalanche forecasting tool is needed. This study confirmed the underlying weather patterns proposed by Hétu (2007) and Fortin et al. (2011) to explain avalanche activity in northern Gaspésie and showed that statistical analysis based on the avalanche inventory program can be used to build a daily snow avalanche forecasting tool. Logistic regression was used to calculate the probability of snow avalanches on a regional and local scale and was then tested to ensure its ability to forecast avalanches on a daily basis.

The models improve our knowledge of the causes of avalanche formation and initiation. Each year, avalanche activity tends to be correlated with total winter snowfall. The importance of snowfall is also reflected in the daily analysis, where daily snowfall the day of the event, or during the 2 days preceding the event, was found to highly control the avalanche formation and initiation. The large scree slopes located along the coast are highly sensitive to snow loading during snowfalls and wind deflation between snow storms. In the valley, slopes are less responsive to snow loading, and 3 days of snow accumulation tends to be the most significant parameter to explain avalanche occurrence. Rain-on-snow events and rainy thaws represent the second most effective scenarios to explain avalanche occurrence. Therefore, liquid precipitation is a highly significant variable when modeling the probability of avalanche occurrence in maritime mountainous areas, as reported by Floyer and McClung (2003), Hendrikx et al. (2005), and Peitzsch et al. (2012).

Logistic models, such as those presented in this paper, are powerful tools for avalanche forecasting and risk management along roads. When tested, the models prove to be an efficient in targeting avalanche days with high levels of activity. If used by an experienced avalanche forecaster, they can also allow the identification of the more probable avalanche days triggered during rainy thaws or by rain-on-snow events. Taking into account the specificity of each site (or road section) aided in the development of more accurate logistic models, but did not prove to be more efficient than the regional model when tested to forecast snow avalanches in an operational perspective. The influence of the weather on the snowpack evolution of each road section or slopes with different geographical and geomorphological contexts should be validated in order to better understand the avalanche formation in this particular climatic region. As mentioned by Fortin et al. (2011), no regular monitoring of the physical properties of the snowpack is currently undertaken along the roads of northern Gaspésie. Since we do not have precise information on the snowpack conditions in this area, future work should study the influence of the weather on the snowpack evolution with an emphasis on the rain-on-snow events and the wind effect on snow loading.

Acknowledgements Many thanks to all employees of the Centre de Service du Ministère des Transports du Québec (MTQ) in Sainte-Anne-des-Monts. This work was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fond québécois pour la recherche nature et technologie (FQRNT).

Appendix

See Figs. 13, 14, 15, 16, 17, 18 and 19

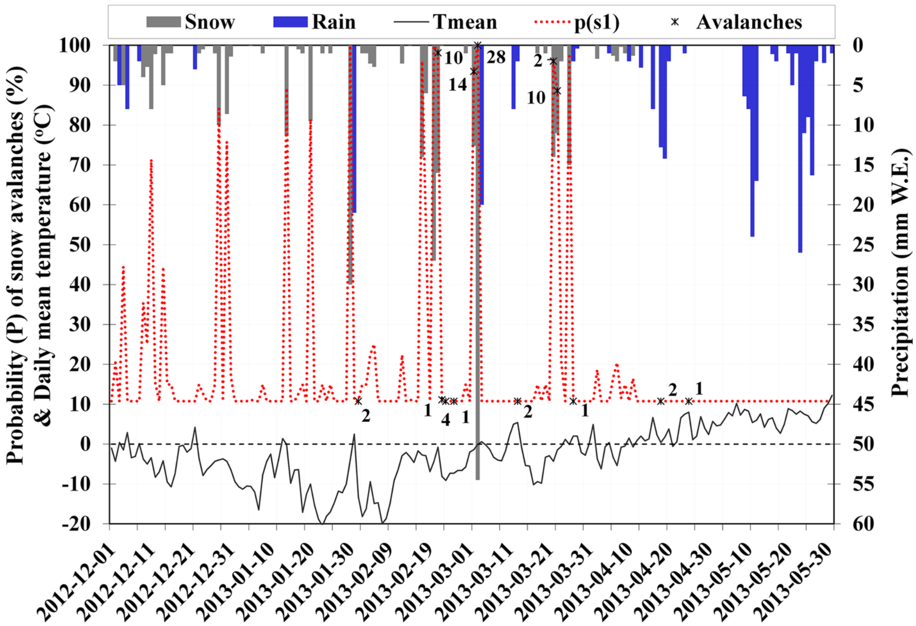

Fig. 13 Logistic model $p(s1)$ used to forecast snow avalanches on roads 132 and 198 (all road sections) in Northern Gaspésie during the winter of 2012–2013

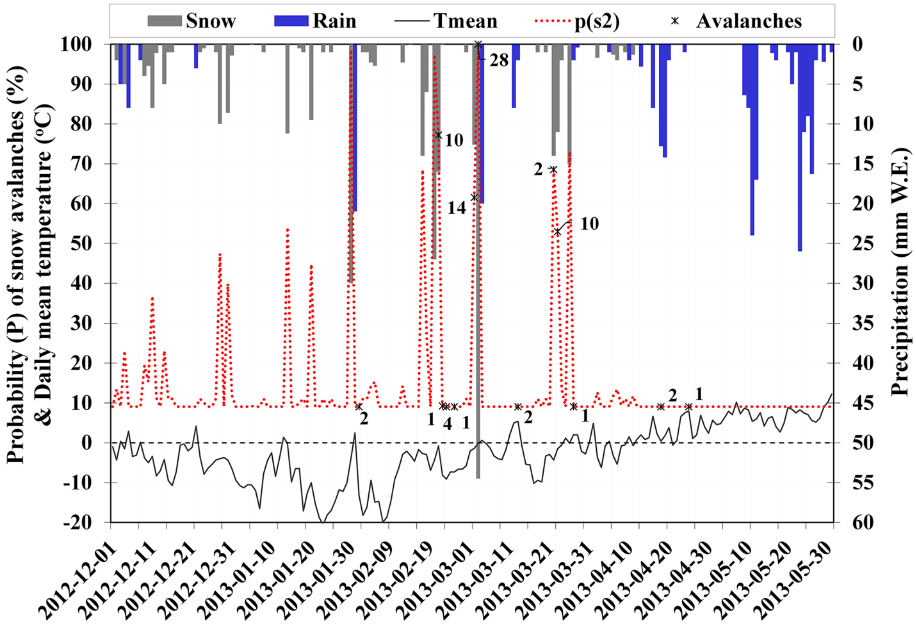

Fig. 14 Logistic model $p(s2)$ used to forecast snow avalanches on roads 132 and 198 (all road sections) in Northern Gaspésie during the winter of 2012–2013

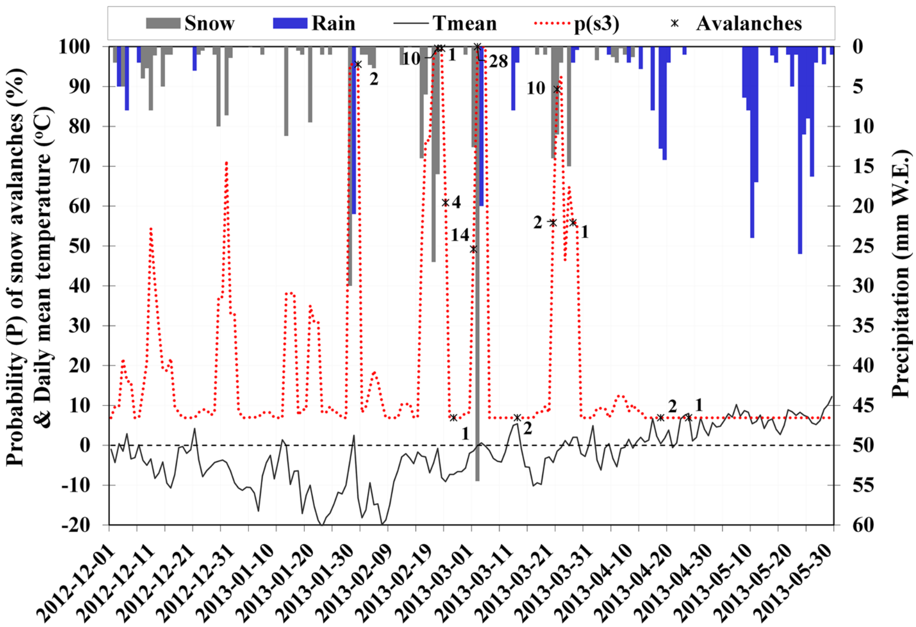

Fig. 15 Logistic model $p(s3)$ used to forecast snow avalanches on roads 132 and 198 (all road sections) in Northern Gaspésie during the winter of 2012–2013

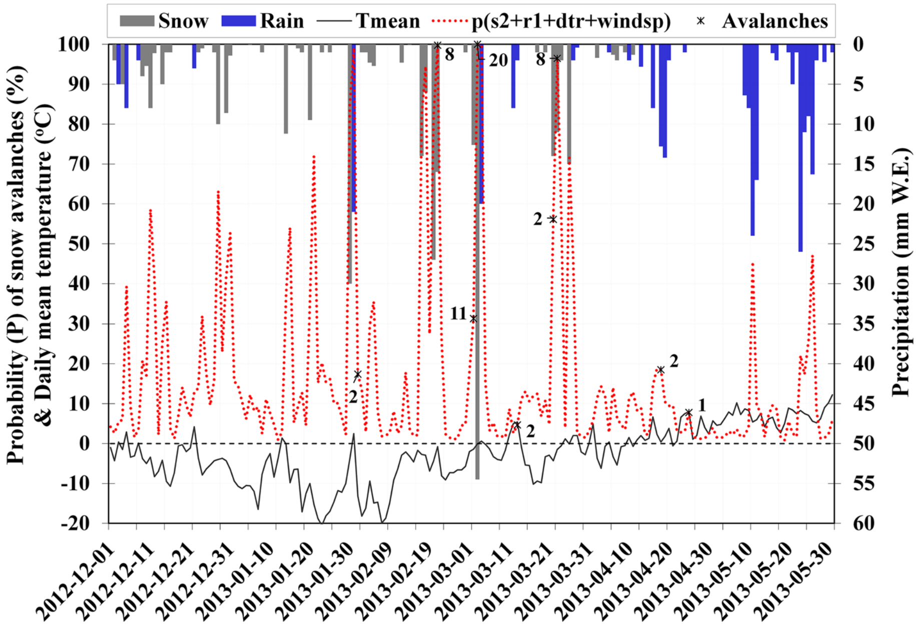

Fig. 16 Logistic model $p(s2 + r1 + \mathrm{dtr} + \mathrm{windsp})$ used to forecast snow avalanches on the road 132 (road sections 50 to 130) in Northern Gaspésie during the winter of 2012–2013

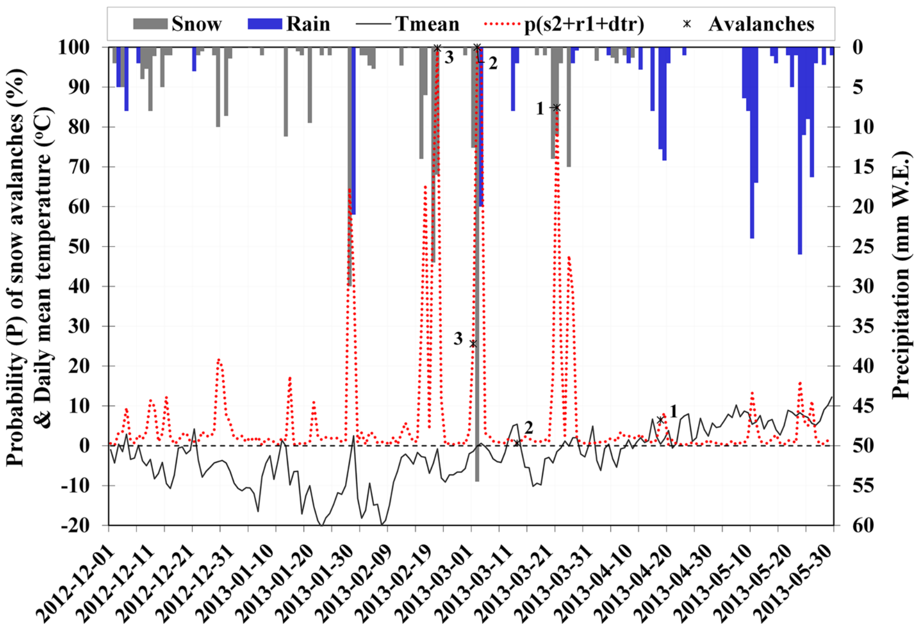

Fig. 17 Logistic model $p(s2 + r1 + \mathrm{dtr} + \mathrm{ftc})$ used to forecast snow avalanches on the road 132 (road section 100) in Northern Gaspésie during the winter of 2012–2013

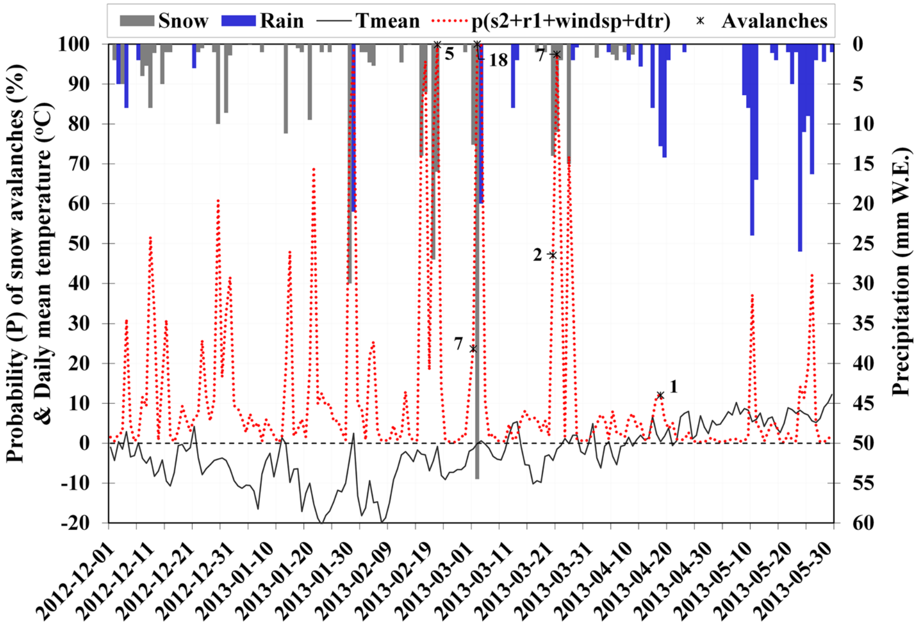

Fig. 18 Logistic model $p(s2 + r1 + \mathrm{windsp} + \mathrm{dtr})$ used to forecast snow avalanches on the road 132 (road sections 120 and 130) in Northern Gaspésie during the winter of 2012–2013

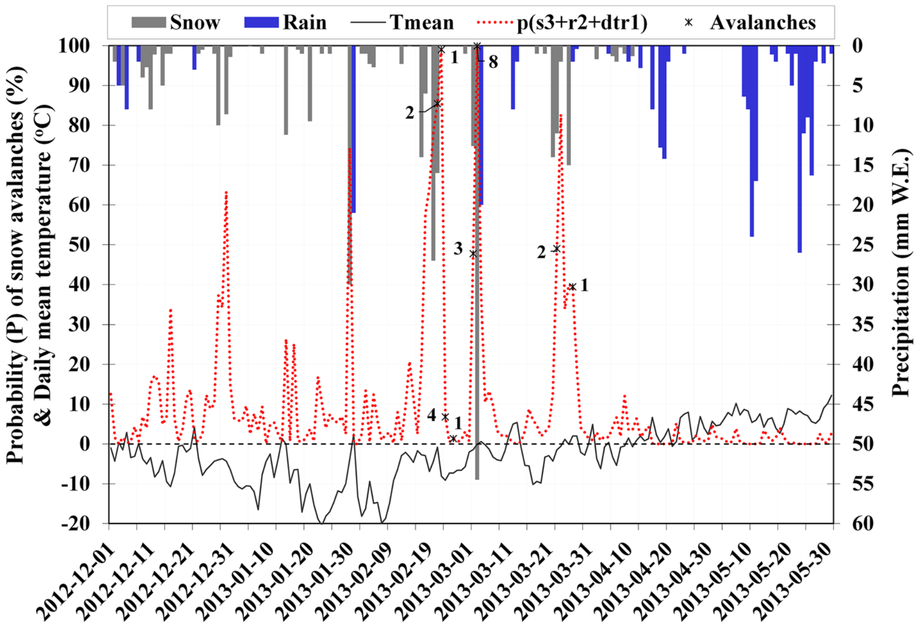

Fig. 19 Logistic model $p(s3 + r2 + \mathrm{dtr1})$ used to forecast snow avalanches on the road 198 (road section 10) in Northern Gaspésie during the winter of 2012–2013

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