STATISTICAL ANALYSIS AND OPERATIONAL AVALANCHE FORECASTING ON THE ROADS OF NORTHERN GASPÉSIE, QUÉBEC, CANADA

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ABSTRACT: Snow avalanches are a major natural hazard for road users and infrastructure in northern Gaspésie (Eastern Canada). Over the past 15 years, the occurrence of 642 snow avalanches on the two major roads servicing the area was reported by the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET). Since 2016, Avalanche Québec (AvQc) issue avalanche bulletins for the MTMDET based on snowpack and weather analysis. As academic contributors, our research focus on analyzing the weather patterns promoting snow avalanche initiation and developing statistical tools to forecast snow avalanches on a daily basis. Using logistic regression (LR) and classification tree (CT) we analyzed 15 years of weather and avalanche data on a regional and local (road sections along the coast and inland) scale. We then test the best LR and CT models over the last three seasons in an operational forecasting perspective: each day, the probability of occurrence (LR) and the prediction (CT) computed by the models were compared to the avalanche hazard issue by AvQc. We also document the model performance using different forecast verification methods. Since most of the avalanche hitting the road seems to be controlled by direct snow loading more than persistent avalanche problems, stochastic models remain a highly effective complementary tool for the forecasters. Finally, we discuss the effects of climate change on avalanche activities.

KEYWORDS: Snow avalanche forecast, logistic regression, classification tree.

1. INTRODUCTION

Snow avalanches are the second most fatal natural hazard in Quebec (80 death) (Hétu et al, 2011). Between 1909 and 1971, five road death were caused by avalanches: two in Charlevoix (1909 and 1936) and three in Gaspésie (1935, 1956 and 1971). In northern Gaspésie, the road is bounded by a series of steep slopes and the St. Lawrence Estuary (Fig. 1 and 7). Most avalanches are reported on the national roads 132 and 198, two major transportation corridors linking the eastern part of the peninsula with the road network of western Quebec. Between 2003 and 2018, 13 road accidents caused by avalanches have been officially reported by the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET), but more minor accidents or cars stuck in snow avalanche deposits are also known to have been observed but not reported (Fig. 1). Before 2016, the MTMDET used avalanche bulletin issued two or three times a week by Avalanche Québec (AvQc) for the Chic-Choc mountain located in the middle of the Gaspésie peninsula. Since 2016, an avalanche forecaster issue avalanche bulletins for the road corridors located along the coast, where weather and snow conditions differ from those of the interior mountain range (Gauthier et al., 2017; Fortin and Hétu 2009, 2013; Fortin et al. 2011; Gagnon 1970).

Establishing strong relationships between weather conditions and avalanche days is one of the first steps toward efficient avalanche forecasting (e.g. 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 (e.g. 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 (Gauthier et al., 2017; Jomelli et al. 2007). The underlying challenge in the development of such forecasting models is the lack of reliable data with which to develop them. The MTMDET database on avalanche activity along the roads of northern Gaspésie now contains 642 events (137 avalanche

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days) reported over 15 avalanche seasons (Fig. 2). A sufficient number of events are therefore available to produce statistical forecasting models. As academic contributors, our research focus on creating and testing statistical tools to forecast snow avalanches on a daily basis.

Figure 1. March 3rd 2013 avalanche on road 132 east of Mont-Saint-Pierre (photo: MTMDET).

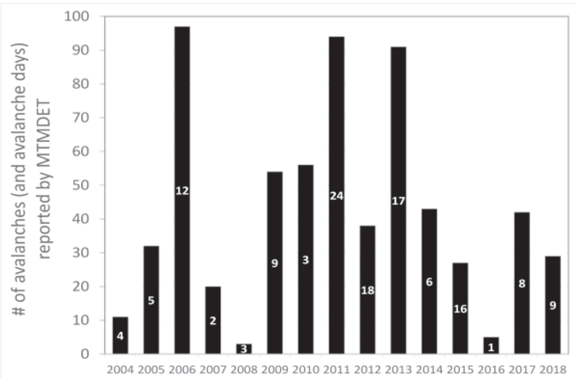

Figure 2. Avalanches and avalanche days reported by the MTMDET since 2004.

2. METHODS

2.1 Study area

The study area is located on the north shore of the Gaspé Peninsula in eastern Canada (Fig. 3). It covers 70 km of national road 132, between Tourelle and Manche d'Épée, and the first 6 km of national road 198, south of L'Anse-Pleureuse. The annual average daily traffic (AADT) varies from 2000 to 5000 vehicles at the junction of roads 132 and 198 and between 200 and 500 heavy load trucks, including wind turbine transportation. The regional snow climate is characterized by many extreme changeover: 1) continental low pressure systems that usually comes with strong northeastern wind and snow accumulation of up to 100 cm in 48 hours, cold Arctic air mass bringing strong northwestern wind followed by many days with temperature below -20°C and mid-season warm spell with few rainy-thaw days.

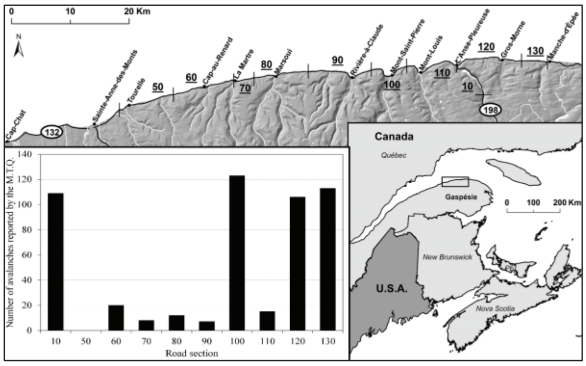

Figure 3. Study area and the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET) road section.

2.2 Avalanche and meteorological database

The database used in this study is part of a larger slope movement inventory program started in 1987 by the MTMDET. Since the initiation of the program, a patrol has circulated year-round and 24 hours a day on the roads and has reported rock falls, landslides, ice-block falls and snow avalanches. 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. The MTMDET subdivided routes 132 and 198 into 10 distinct road sections (10, and 50–130 in intervals of 10) (Fig. 3). MTMDET interventions to clear snow deposits from the roads are reported according to these road sections. Since 2004, interventions are recorded in a computerized database.

The Environment Canada weather station in Cap-Madeleine 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 Manche d'Épée (Fig. 3). Even if some orogeny effect increases local precipitation in 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). Meteorological metrics (meaningful variables) for snow avalanche analysis were generated from these data. This list of variable is similar to those used by Gauthier et al. (2017) and Hendrikx et al. (2014) (Table 1).

2.3 Statistical analysis

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, the statistical model were created 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 (Fig. 3). In each case, the effect of meteorological variables on snow avalanche activity was simulated using Classification tree (CT) and logistic regression (LR) models.

We used the last 15 years (2004-2018) of data to analyze the weather patterns promoting snow avalanche initiation. The first 12 years (2004-2015) were used to create the statistical models and the last three years (2016-2018) were used to test the models. We use the methodology proposed by Hendrikx et al. (2014) to create and test the CT model. We kept a similar approach to develop the LR model (see also Gauthier et al., 2017). To describe and compare the different models performance we used different evaluation metrics as defined in the contingency table (Table 2). We also derived the negative predictive value (NPV), the positive predictive value (PPV), the accuracy (ACC) and the area under curve (AUC) of the receiver operating characteristic (ROC) from the contingency table.

Table 1. Meteorological parameters used in the analysis and obtained from the Environment Canada weather station in Cap-Madeleine.

Parameters	Description
tmoy, tmoy-1, tmoy-2, ..., tmoy-7	Daily average temperature and up to 7 days prior (°C)
tmax, tmax-1, tmax-2, ..., tmax-7	Daily maximum temperature and up to 7 days prior (°C)
tmin, tmin-1, tmin-2, ..., tmin-7	Daily minimum temperature and up to 7 days prior (°C)
ecartt, ecartt-1, ecartt-2, ..., ecartt-7	Daily temperature range and up to 7 days prior (°C)
ftc, ftc-1, ftc-2, ..., ftc-7	Dailly freeze-thaw cycle and up to 7 days prior (ftc = 0 or 1)
intgel, intgel-1, intgel-2, ..., intgel-7	Dailly freezing intensity and up to 7 days prior (°C)
djfonte	Melting degree-days (°C)
ptot	Daily total precipitation (mm WE)
r24, r48, ..., r120	Sum of rain over 24 to 120 hours (mm)
s24, s48, ..., s120	Sum of snow over 24 to 120 hours (mm WE)
ventvit, ventvit-1, ventvit-2, ..., ventvit-7	Daily maximum windspeed and up to 7 days prior (km/h)
wdindex, wdindex-1, wdindex-2, ..., wdindex-7	ventvit * ptot and up to 7 days prior
wdindex3, wdindex3-1, wdindex3-2, ..., wdindex3-7	$ventvit^3$ * ptot and up to 7 days prior

Table 2. Contingency table for our evaluation metrics.

		Observed		
		Non-avalanche day (0)	Avalanche day (1)	% Correct
Predicted	Non-avalanche day (0)	a: Correct non event	b: Misses	a / a+b: Negative predictive value (NPV)
	Avalanche day (1)	c: False alarm	d: Hits	d / c+d: Positive predictive value (PPV)
				a+d / a+b+c+d: Accuracy (ACC)

3. RESULTS

At this point, we will focus on presenting the best regional (all road sections) forecasting model and compared the CT and LR models. Our best LR model only used three parameters (Fig. 4): sum of snow in 48 hours (s48), sum of rain in 24 hours (r24) and daily average air temperature one day prior (tmoy-1). It shows an accuracy of 84% (Table 3) and an AUC of 0,917 (Fig. 4). After pruning our best CT to keep the three best parameters, we ended with the same parameters as for the LR, an ACC of 73% and an AUC of 0,823 (Fig. 5 and Table 3).

The CT and LR models were tested on the three last avalanche season (2016, 2017 and 2018) and compared with AvQc hazard forecast for the area: four level of danger (low, moderate, considerable and high). Preliminary results with the LR model shows extremely good concordance with the hazard forecast issued by AvQc and good forecasting potential with an ACC of 83% (Fig. 6). Further analysis are still needed.

Table 3. Classification matrix for Logisitic regression (LR) and Classification Tree (CT) models.

Logistic Regression (LR)		Observed		
		Non-avalanche day (0)	Avalanche day (1)	% Correct
Predicted	Non-avalanche day (0)	500	66	88.34%
	Avalanche day (1)	117	449	79.33%

Classification Tree (CT)		Observed		
		Non-avalanche day (0)	Avalanche day (1)	% Correct
Predicted	Non-avalanche day (0)	556	10	98.23%
	Avalanche day (1)	296	270	47.70%

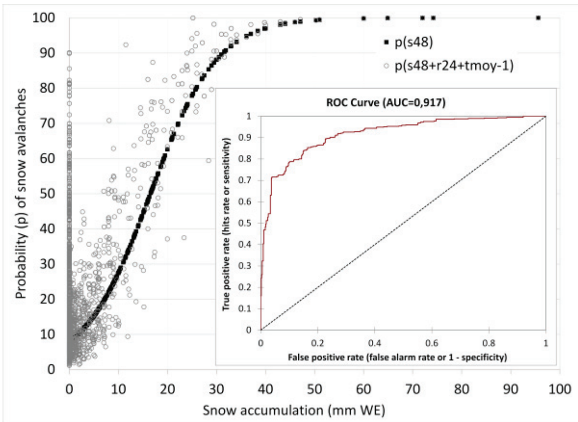

Figure 4. Probability of avalanches for all road sections and the receiver operating characteristic (ROC) curve.

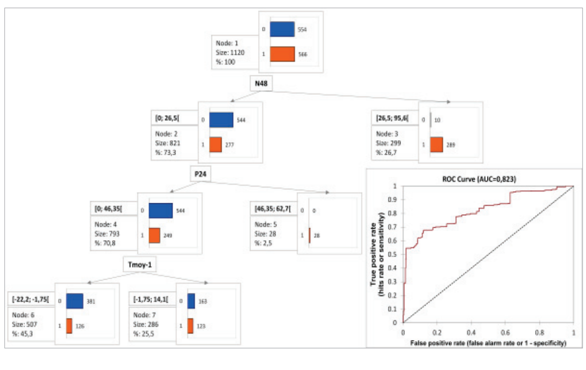

Figure 5. Classification tree for all road sections and the receiver operating characteristic (ROC) curve.

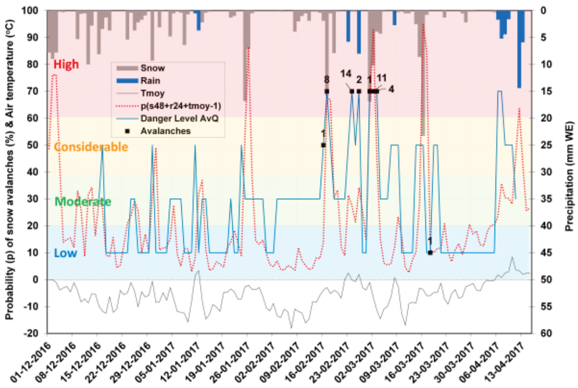

Figure 6. Logistic regression (LR) model p(s48, r24, tmoy-1) used to forecast snow avalanches on roads 132 and 198 (all road sections) in northern Gaspésie during the winter of 2016–2017.

DISCUSSION CONCLUSION

In early season, few avalanches are reported by the MTMDET (Fig. 6). Most of them are trapped in man-made bunds and ditches along the road (Fig. 7). 40 to 50 mm in snow water equivalent (SWE) is generally needed to fill the bund (Gauthier et al., 2017). This can explain most false alarm (high probability of occurrence and no avalanche) given by the LR model in December and January (Fig. 6).

Two types of avalanche regime have been point it out along the coast of northern Gaspésie (Hétu, 2007; Fortin et al., 2011; Gauthier et al., 2017). 90% of all avalanches comes from direct snow accumulation of around 20 to 25 mm SWE in 48 h. This triggering threshold shows good concordance with the one calculated with the CT (Fig. 5). The second major avalanche problem (8%) are rain-on-snow events or avalanche triggered after prolonged thaw (spring or winter spell) or avalanche triggered by ice-block fall (Graveline and Germain, 2017). Both models take into account meaningful metrics representing this type of avalanche problem (r24 and tmoy-1). However, the model seems to underestimate the effect of rain-on-snow as a triggering factor: the threshold given by the CT may be too high (r24 > 46 mm) (Fig. 5). This may also explain the misses (avalanche day not predicted) on February 24th and 26th 2017 (Fig. 6). We believe climate change may increase the number of avalanche triggered by rain-on-snow and during prolonged winter spell since these meteorological events tend to be more frequent (Fig. 8).

Both LR and CT prove to be efficient tools to forecast days with high levels of snow avalanches activity. In very few cases (< 2%), the models were too reactive and were not able to predict after storm avalanches triggered on persistent layers.

Since the slope shows almost instantaneous response to snow loading the LR and CT models are promising forecasting tools for operational avalanche forecaster in northern Gaspésie. However, AvQc forecasters feel that the model did not reflect the real complexity of the snowpack evolution and spatial variability. Refinement and validation are still needed and further research should focus on: 1) the weather patterns promoting snow avalanche initiation; 2) the snowpack spatial variability between the coastal slope highly exposed to wind deflation (road 132) and the inland valley slope (road 198); 3) the rain-on-snow and the effect of climate change on the snowpack and avalanche dynamic.

Figure 7. Snow avalanche accumulation in road side bund.

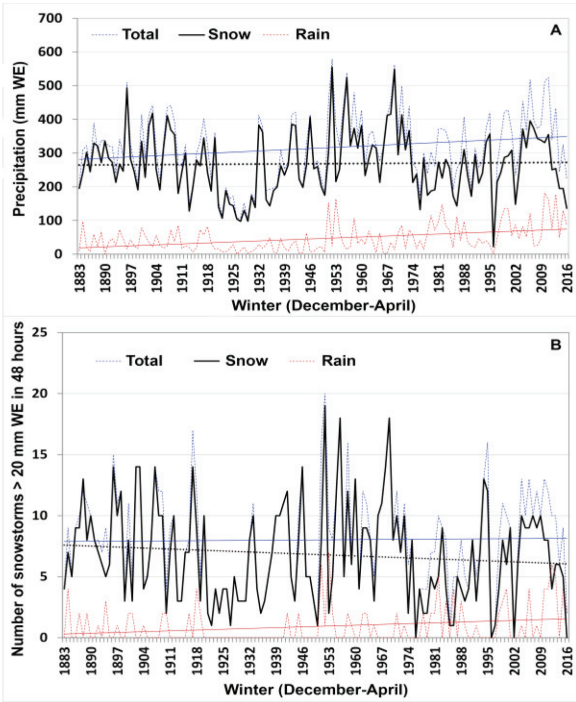

Figure 8. Winter precipitation (total, snow and rain) since 1883 (A) and the number of snowstorm exceeding 20 mm WE in 48 hours since 1883 (B).

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