Université du Québec
à Rimouski

VARIABILITÉ SPATIO-TEMPORELLE DES PROPRIÉTÉS DU MANTEAU NEIGEUX DANS UN CONTEXTE OPÉRATIONNEL DE PRÉVISION DES AVALANCHES, GASPÉSIE, CANADA

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PAR

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AVANT-PROPOS

La recherche scientifique est une passion qui m'habite depuis le début de mon parcours universitaire. Je pensais déjà au titre de mon mémoire alors que je n'avais pas fini ma première année de baccalauréat. C'est lors de ma certification d'opérateur professionnel d'avalanche Niveau 1 de l'Association canadienne des avalanches que l'idée d'étudier la variabilité spatiale des propriétés de la neige a commencé à habiter mon esprit. J'étais seulement en deuxième année de baccalauréat, mais j'avais déjà mon sujet de maîtrise. Il ne me restait plus qu'à convaincre un directeur de recherche avec de l'argent… Heureusement, Francis Gauthier a bien voulu donner une chance à un jeune étudiant qui se voyait déjà chercheur, mais qui ne s'est pas écrire. Le choix de produire deux articles scientifiques était pour moi un défi que je désirais relever, pour me prouver à moi-même que j'étais capable de faire de la recherche. Ce choix a été un apprentissage long, difficile et parfois décourageant, mais il m'a permis de découvrir l'expérience complète de la recherche et de poursuivre au doctorat.

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RÉSUMÉ

Depuis 2002, une prévision du risque d'avalanche de neige est émise pour le secteur skiable du massif des Chic-Chocs et depuis 2016, celle-ci élargit son offre de service quotidienne aux versants avalancheux qui bordent les routes 132 et 198 dans le nord de la Gaspésie. À l'heure actuelle, l'un des plus grands défis en prévision des avalanches est d'expliquer la variabilité spatiale des propriétés du manteau neigeux. Aucune étude n'a documenté cette problématique pour les secteurs d'opérations d'Avalanche Québec. L'objectif principal du projet est de documenter la variabilité spatiotemporelle des propriétés du manteau neigeux pour les deux secteurs d'opérations d'Avalanche Québec et repose sur les trois objectifs spécifiques suivants : 1) Caractériser le climat de neige et d'avalanche pour la péninsule gaspésienne 2) analyser la variabilité spatiale entre les données météorologiques et de propriétés du manteau neigeux entre un versant côtier (132) et un versant situé dans une vallée (198). 3) estimer la variabilité spatiale de l'accumulation de neige pour chacun des versants à l'étude en utilisant la géostatistique avec une attention particulière à la distribution de la végétation. Les résultats suggèrent un climat de neige et d'avalanche contrasté avec des hivers continentaux et maritimes, un manteau neigeux froid et mince, ainsi qu'une faible présence de problème persistant d'avalanche. La similitude avec le Mont Washington et les Alpes Centrales japonaises supportent l'idée d'agrandir la description du climat de type Transition pour inclure le climat de neige *Rainy Continentale*. Pour l'objectif deux, des analyses de séries temporelles révèlent une variabilité pour le régime de vent (vitesse et direction) et de bilan radiatif de surface, entre les deux sites d'étude (côte/vallée). À l'échelle de la pente, des analyses géostatistiques exposent l'influence de la végétation sur les patrons spatiaux d'accumulation de neige. Ces connaissances sur la variabilité spatiotemporelle du manteau neigeux devraient améliorer la fiabilité de la prévision et du programme futur d'atténuation des avalanches de neige.

Mots clés : Climat de neige, propriétés du manteau neigeux, variabilité spatiotemporelle, péninsule gaspésienne, avalanche de neige, prévision des avalanches.

ABSTRACT

Since 2002, avalanche forecasts are released for the skiing area of the Chic-Chocs mountain range by Avalanche Québec and recently in 2016, the organization expanded its services to avalanche-prone slopes on provincial roads 132 and 198 of northern Gaspésie. One of the biggest challenges in avalanche forecasting is to assess the spatial variability of snowpack properties in order to evaluate the stability of a slope. No study has focused on the spatial variability for forecast areas of Avalanche Québec. The absence of such knowledge in the area makes the forecasting complex. The principal objective is to assess the spatiotemporal variability of snowpack properties for the two operational areas of Avalanche Québec and rely on these three specific objectives: 1) describe the snow and avalanche climate for the Gaspé Peninsula; 3) analyse the variability of meteorological data and snowpack properties between coastal (132) and valley avalanche-prone slope (198); 3) estimate spatial variability of snow accumulation using geostatistical analysis for each study sites with specific attention regarding vegetation distribution. The results suggested contrasted snow-climate with continental and maritime winters, a cold and thin snowpack and a low annual percentage of persistent type of avalanche problem. We compared our results with data from Mt Washington, the Central Japanese Alps and propose to expand the Transitional snow-climate while including the term *rainy continental* snow climate for the Gaspé Peninsula. For the the second objective, time-series analysis shows specific wind pattern and radiation budget between the coastal and the valley site. At the slope scale, geostatistical analysis show the influence of the vegetation on snow accumulation spatial pattern. Proper knowledge on spatial variability and specifically snow deposition is required in order to make reliable avalanche forecast and mitigation program.

Keywords: Snow climate, snowpack properties, spatiotemporal variability, Gaspé Peninsula, snow avalanche, avalanche forecasting.

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LISTE DES ABRÉVIATIONS, DES SIGLES ET DES ACRONYMES

MTQ Ministère des Transports du Québec

LGGRM Laboratoire de Géomorphologie et de Gestion des Risques en Montagne.

EEN/SWE Équivalent en Eau de la Neige / *Snow Water Equivalent*.

INTRODUCTION GÉNÉRALE

1.1 ÉTAT DES CONNAISSANCES

1.1.1 Climat hivernal gaspésien

La péninsule gaspésienne est une région située dans la province de Québec, au Canada. Le climat gaspésien s'inscrit dans la grande zone tempérée froide de la classification de Köppen, avec un climat continental humide, été tempéré (Dfb), où la température moyenne annuelle est de 3 °C (Gagnon, 1970). Il y tombe environ 800 mm de précipitations annuelles sur la côte et jusqu'à 1500 mm dans le massif des Chic-Chocs, dont 35% tombent sous forme de neige (Gagnon, 1970). Le climat gaspésien est un climat hybride où se conjuguent des influences maritimes, continentales et orographiques (Gagnon, 1970). La proximité du golfe du Saint-Laurent influence grandement le climat du nord de la Gaspésie. Le centre de la péninsule est caractérisé par le massif des Chic-Chocs culminant à plus de 1100 m d'altitude, permettant la mise en place d'un gradient altitudinal sur le plan des températures et des précipitations (Gagnon, 1970). De décembre à avril, la station météorologique Cap-Madeleine, située sur la côte à 20 m d'altitude, reçoit en moyenne 307 mm de précipitations totales, incluant 60 mm de pluie, et -6.5 °C de température moyenne hivernale (normale climatique 1971-2000) (Fortin *et al.*, 2011). La station météorologique de Cap-Seize, située à mi-chemin entre les Chic-Chocs et la côte à 229 m d'altitude, reçoit en moyenne 470 mm de précipitations totales, incluant 87 mm de pluie, et une température moyenne hivernale de -8.5 °C (normale climatique 1971-2000) (Fortin & Hétu, 2009). Ces données climatiques (1971-2000) montrent une partie de l'effet de ce gradient altitudinal et de distance par rapport au fleuve (Fortin & Hétu, 2013). Fortin & Hétu (2010) ont également montré la présence d'un gradient altitudinal pour trois propriétés du manteau neigeux : l'épaisseur, la densité et l'EEN (Équivalent En Eau), plus importante en altitude. Cependant, ces données climatiques et de propriétés du manteau sont des moyennes qui procurent peu d'informations utiles à la caractérisation du régime d'avalanches.

Le Nord de la péninsule gaspésienne est principalement influencé par deux types de masses d'air d'où résulte des conditions météorologiques contrastées : 1) masse d'air arctique pouvant faire baisser les températures jusqu'à -30 °C et 2) masse d'air chaud et humide avec des précipitations et/ou des températures près du point de congélation (Fortin & Hétu, 2013; Gauthier *et al.*, 2017).Ces conditions météorologiques affectent les propriétés de la neige, notamment la formation de couches de glace qui composent environ 30 % du manteau neigeux (4 couches de glace en moyenne par profil) (Fortin & Hétu, 2009). Ces couches de glace, soumises à des températures froides, sont susceptibles de favoriser la formation de cristaux à face plane en périphérie de la couche de glace et de constituer une couche faible, propice à la formation d'avalanches (Jamieson, 2006). Cependant, aucune étude n'a documenté le type de cristaux de neige et le rôle de certains types de cristaux responsables de la formation d'avalanches pour la péninsule gaspésienne, contrairement à l'Ouest canadien (Haegeli & McClung, 2007). Les propriétés de la neige décrites dans ces études sont principalement des moyennes issues de plusieurs mesures d'un profil de neige comme la densité ou l'EEN (e.g. Fortin & Hétu, 2010). Alors que les propriétés du manteau neigeux décrivant une instabilité neigeuse sont plutôt des exceptions précises, par exemple une couche de faible densité de deux millimètres d'épaisseur, surmontée d'une plaque cohésive de plusieurs centimètres (Schweizer *et al.*, 2003). Cet arrangement stratigraphique spécifique à la formation d'avalanches est le résultat de plusieurs processus météorologiques et ceux-ci ont été peu documentés sur la péninsule gaspésienne. La compréhension de la variabilité spatiotemporelle de ces processus météorologiques, plus précisément des effets locaux de vallée et côte, mais également entre le massif des Chic-Chocs et la côte, est nécessaire pour caractériser la spécificité climatique hivernale de la péninsule gaspésienne.

1.1.2 Classification du climat de neige

Les classifications de climat de neige ont été développées pour régionaliser des secteurs où les conditions climatiques qui influencent certaines propriétés du manteau neigeux sont similaires. Dans un contexte de prévision des avalanches, ces climats de neige décrivent des propriétés du manteau neigeux, en s’appuyant sur des moyennes saisonnières, pour déterminer le type de régime d’avalanches (LaChapelle, 1965). Ces climats de neige ont d’abord été décrits de façon qualitative sur la côte ouest-américaine sous trois différents types de climats de neige : maritime, continental et de transition (Armstrong & Armstrong, 1987; LaChapelle, 1965; McClung & Schaerer, 2006; Mock & Birkeland, 2000). Ces différents types de climats de neige sont caractérisés par des conditions climatiques spécifiques, et de cela en découle une façon d’appréhender les avalanches de neige dans ces régions (McClung & Schaerer, 2006). Le climat de neige maritime est caractérisé par des chutes abondantes de neige et des températures qui oscillent près du point de congélation. Les instabilités présentes dans le manteau neigeux sont liées à l’accumulation rapide de neige et se situent principalement dans la partie supérieure du manteau. La prévision des avalanches adaptée à ce type de climat s’appuie principalement sur l’observation des conditions météorologiques (McClung et Schaerer, 2006). Le deuxième type de climat est continental, caractérisé par de faibles chutes de neige et des températures froides. Il en résulte un manteau neigeux avec des couches faibles persistantes tout au long de la saison. Ces couches faibles persistantes peuvent se situer à tous les niveaux du manteau neigeux. La prévision des avalanches s’appuie sur l’observation du manteau neigeux et d’un suivi des couches faibles persistantes (McClung et Schaerer, 2006). Le troisième type de climat, de transition est un climat hybride entre le maritime et le continental, où des périodes avec des températures froides favorise la formation de couche faible persistante, mais sont également accompagnées de période de fortes précipitations neigeuses. Le caractère hybride de ce troisième type de climat de neige demeure général et uniquement décrit dans l’ouest de l’Amérique du Nord. D’autres régions où se conjuguent différemment des influences continentales et maritimes devraient être caractérisées, et possiblement intégrées dans ce type de climat de neige.

Mock & Birkeland (2000) ont développé un algorithme de classification de climat de neige pour l’Ouest américain (Figure 1). Cet algorithme utilise des données météorologiques sur un hiver complet de décembre à mars, en calculant divers paramètres de classification pour décrire les processus nivologiques spécifiques à la formation d'avalanche (développement de couche faible). Ces paramètres de classification sont des moyennes saisonnières de précipitation liquide/solide, de température de l’air et de gradient de température de neige moyen en décembre. Cet algorithme de classification permet, par exemple, de différencier les hivers où l’accumulation de neige importante et la température près du point de congélation (hiver maritime) décrivent davantage le régime d’avalanches que la métamorphose de la neige (hiver continental). Cet algorithme de classification est utilisé sur plusieurs hivers pour en dégager une tendance générale. Cependant, Schweizer *et al.* (2003) ont démontré que les propriétés du manteau neigeux, à la plaque et à la couche faible, sont les principaux indicateurs de la formation d’avalanches. Haegeli & McClung (2007) proposent d’ajouter différents types de données stratigraphiques sur la plaque et la couche faible, ainsi que des données observations d’avalanche pour décrire les climats de neige. Ils ont également proposé de plutôt utiliser le terme « régime hivernal d’avalanches » pour dissocier ces types de climats de neige (avalanche) à ceux développés en hydroclimatologie.

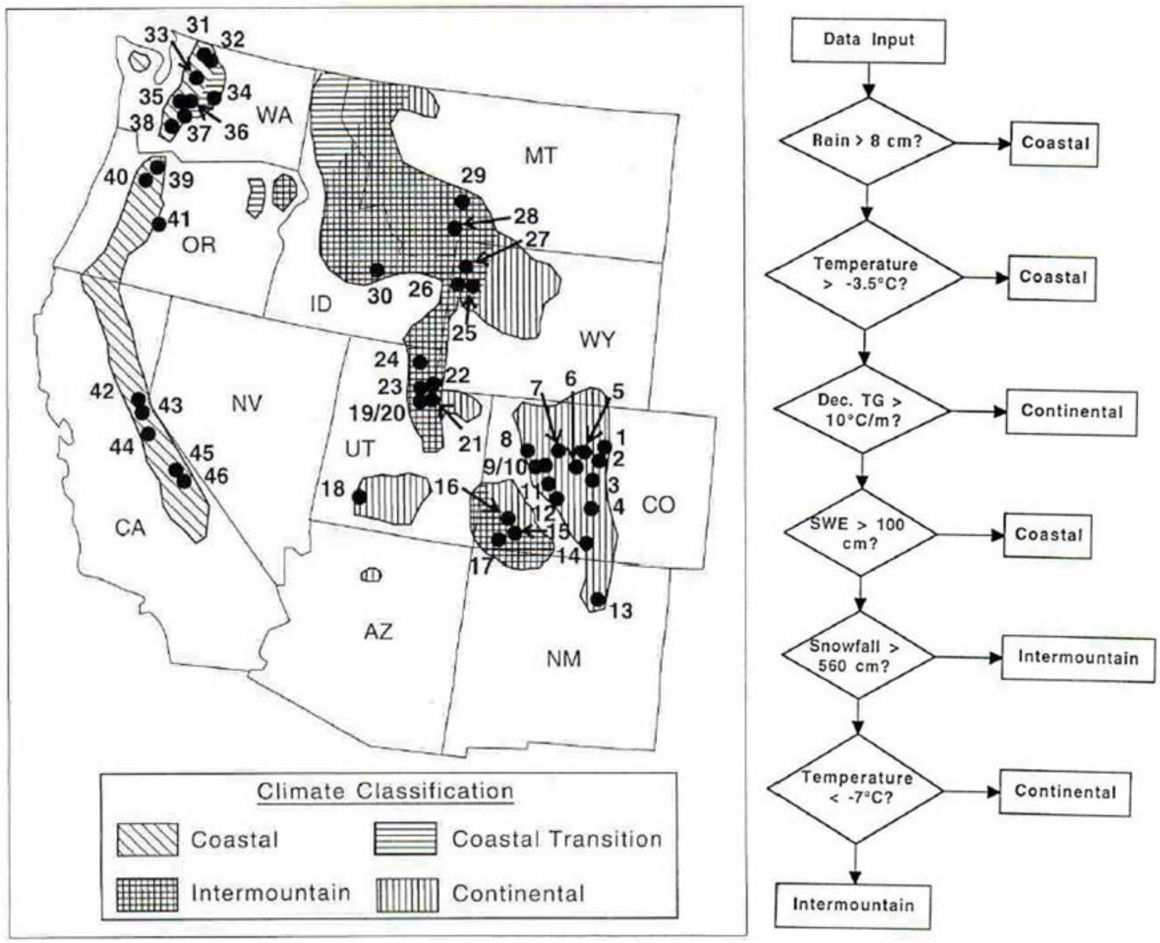


Figure 1. Classification des différents types de climats d’avalanche de neige pour l’Ouest américain selon l’algorithme de classification de Mock & Birkeland (2000). Les chiffres sont les numéros des stations utilisées dans l’article de Mock & Birkeland (2000).

Les climats de neige développés en hydroclimatologie visent à décrire des propriétés nivales de moyennes saisonnières reliées à la teneur en eau liquide du manteau neigeux pour des fins de gestions de la ressource en eau. La caractérisation à partir des moyennes saisonnières de la teneur en eau et de sa hauteur n’est pas pertinente pour décrire des régimes d’avalanche de neige. Cependant, une composante du système de classification de Sturm *et al.* (1995) peut être intéressante dans le cadre de ce travail, car elle permet décrire un manteau neigeux dans un contexte de formation d’avalanches, autant qu’en hydroclimatologie. Cette composante utilise les propriétés physiques du manteau neigeux suivantes : hauteur de neige, température, pourcentage de givre de profondeur et pourcentage de couches de glace. Plus récemment, Shandro & Haegeli (2018) ont utilisé des données de prévision des avalanches qui sont les problèmes d'avalanche. Ceux-ci décrivent le type du problème d'avalanche, la probabilité de déclenchement, la distribution spatiale ainsi que la taille probable de l'avalanche (Statham *et al.*, 2018). L'utilisation de ce type de données permet de bien caractériser la nature et le type de danger d'avalanche. Shandro & Haegeli (2018) ont également combiné ce nouveau type de données avec l'algorithme de classification de Mock & Birkeland (2000), pour décrire le régime hivernal d'avalanches de l'Ouest canadien. Différentes méthodes et combinaison de ces méthodes ont été développées pour décrire, d'abord un climat de neige, puis des régimes hivernaux d'avalanches. Ces méthodes utilisent des données météorologiques sur plusieurs hivers, des données décrivant des propriétés physiques du manteau neigeux et des données de prévision des avalanches qui reflètent le type et la nature du danger d'avalanche. Aucune méthodologie intégrant tous ces types de paramètres de classification n'a été utilisée à ce jour.

Certaines régions à travers le monde ont été décrites à l'aide de ces différents paramètres de classification, parfois seule ou ensemble. Eckerstorfer & Christiansen (2011) ont utilisé des données météorologiques ainsi que des données sur les propriétés physiques du manteau neigeux pour décrire la région entourant la ville de Longyearbyen au Svalbard. Ils ont proposé le nom « Haut-Arctique maritime » pour un nouveau climat de neige et d'avalanche. Ce climat est hybride, mais différent du climat de transition (intermontagne) classique observé dans l'ouest de l'Amérique de Nord. Selon Eckerstorfer & Christiansen (2011), les conditions climatiques y sont plus froides et sèches que dans un climat de transition et continental: des températures moyennes annuelles froides (-7 °C), une faible quantité de précipitations totales annuelles (200 mm EEN) et la présence de pergélisol. Les données météorologiques sont seulement présentées pour l'année entière et non pour la saison hivernale, ce qui rend difficile la comparaison avec la méthode proposée par Mock & Birkeland (2000). Eckerstorfer & Christiansen (2011) ont également décrit les propriétés physiques du manteau neigeux avec la méthode de Sturm *et al.* (1995). Leurs résultats indiquent un manteau neigeux froid, occasionnant une forte métamorphose avec une forte présence de givre de profondeur, caractéristique d'un climat continental. Ils ont également constaté la présence de plusieurs couches de glace indiquant une influence maritime. Ikeda *et al.* (2009) ont décrit les Alpes centrales et côtières japonaises en utilisant l'algorithme de classification de Mock & Birkeland (2000). Sur la côte de la mer japonaise, les hivers ont tous été classés maritimes avec des accumulations de neige au-dessus de 1000 mm d'EEN en hiver. Pour les Alpes centrales japonaises, il s'agit plutôt d'hivers continentaux et maritimes, sans hiver de type transition comme résultat de classification avec la méthode Mock & Birkeland (2000) (Ikeda *et al.*, 2009). Les hivers de type continentaux ont été classés par le critère de gradient de température en décembre au-dessus de 10 °C/m et la température moyenne hivernale en dessous de -7 °C. Les hivers maritimes ont été classés par le critère de pluie au-dessus de 80 mm (Ikeda *et al.*, 2009). Ils ont également ajouté à leur méthodes de classification des informations sur les propriétés physiques de la neige. Pour les Alpes centrales japonaises, le manteau neigeux est généralement constitué de grains à face planes et de givre de profondeur, ainsi que de grains de fonte. Comme au Svalbard, ces deux types de grains montrent l'influence continentale et maritime de la région (Eckerstorfer & Christiansen, 2011; Ikeda *et al.*, 2009). Les études sur ces deux régions proposent une méthodologie intéressante pour décrire un climat de neige et d'avalanche, en plus de soulever le fait que certaines régions ne peuvent intégrer les trois principaux climats de neige. Ces régions pourraient, apparentées au climat de neige de la péninsule gaspésienne.

Aucune étude ne documente actuellement le climat de neige et d'avalanche de la péninsule gaspésienne. Une étude à ce sujet permettrait de situer globalement cette région et d'améliorer son mode de gestion et de prévention des risques d'avalanche de neige. L'algorithme de classification de Mock & Birkeland (2000) est utilisé dans plusieurs articles (Haegeli & McClung, 2007; Hägeli & McClung, 2003; Ikeda *et al.*, 2009; Shandro & Haegeli, 2018), mais ceux-ci suggèrent ou ont utilisé d'autres types de données décrivant la neige et le type d'instabilité pour mieux décrire le climat de neige et d'avalanche. Aucune méthodologie inclusive sur le plan des conditions météorologiques, de la stratigraphie et des problématiques d'avalanches, n'est utilisée dans la littérature.

1.1.3 Régime d’avalanches de la péninsule gaspésienne

La méthodologie répertoriée dans la littérature consiste à reconstituer les évènements d’avalanches de neige à partir de différentes méthodes pour en étudier les facteurs de déclenchement, principalement météorologique. Ces reconstitutions d’évènements d’avalanches de neige peuvent se faire à partir de la dendrochronologie (e.g. Boucher *et al.*, 2003) ou avec la banque d’évènements historiques de mouvement de terrain du MTQ (e.g. B Hétu, 2007).

Littoral nord de la péninsule gaspésienne

Les analyses faites pour ce secteur ont majoritairement été établies à partir de la banque de données du MTQ. Les journées où des avalanches ont été observées sont identifiées comme étant une journée avalancheuse, constituant une variable binaire (absence/présence d’évènements). À partir de ces journées avalancheuses, des analyses graphiques (Fortin *et al.*, 2011; B Hétu, 2007) et statistiques (Fortin *et al.*, 2011; Gauthier *et al.*, 2017; Graveline & Germain, 2016) ont permis d’identifier les variables explicatives (condition météorologique) du déclenchement d’avalanche de neige. La taille et le nombre d’avalanches dans une journée ne sont pas pris en compte contrairement à Schweizer *et al.* (1998) qui a pondéré les journées d’avalanches en fonction de la taille des avalanches observées. L’application de cette méthode dans la région à l’étude aurait permis de déterminer les variables météorologiques responsables des avalanches naturelles et cycles d’avalanches naturelles de fortes magnitudes. À l’échelle annuelle, les années avec de fortes activités avalancheuses représentent des saisons hivernales avec des accumulations de neige plus élevées que la normale climatique (Dubé *et al.*, 2004). Cependant, quatre années sont au-dessus des normales climatiques d’accumulations de neige sans toutefois être des années avec une forte activité avalancheuse (Dubé *et al.*, 2004).

Le littoral nord est influencé par de nombreux redoux hivernaux et des tempêtes de neige. Ces évènements météorologiques ont une influence sur le régime local d’avalanches. Deux régimes météorologiques d’avalanches semblent se distinguer : un régime de fonte et de tempêtes hivernales (Fortin *et al.*, 2011; B Hétu, 2007). B Hétu (2007) soupçonne également le rôle des croûtes de regel avec le développement de grains à face plane qui pourraient causer des couches faibles persistantes. Selon le même auteur, le vent serait un facteur réducteur d'instabilité, par déflation éolienne. Fortin *et al.* (2011) propose également des régimes d'avalanches de neige catégorisés par contexte géomorphologique qui possèdent un régime d'enneigement particulier. Le premier est le régime de talus d'éboulis côtier qui entraîne trois conséquences majeures sur le régime d'enneigement et d'avalanches : « 1) les talus d'éboulis côtiers n'arrivent pas à développer un épais manteau neigeux, ce qui rend peu probable les avalanches en différé reliées à la métamorphose de la neige ; 2) entre les chutes de neige, la probabilité que survienne une avalanche diminue très rapidement ; 3) les avalanches dépendent directement des précipitations» (Fortin *et al.*, 2011). Le régime de talus d'éboulis côtier est donc soumis au régime de fonte et aux tempêtes hivernales, mais réagit rapidement aux évènements météorologiques. Les causes de cette réponse rapide au déclenchement d'avalanches n'ont pas été étudiées. Le régime d'avalanches dans des couloirs forestiers à carapace de glace est soumis à tous les types de régimes météorologiques, soit le régime de tempêtes hivernales et de fonte (Fortin *et al.*, 2011). Ces couloirs sont bordés de forêts favorisant l'accumulation de la neige et la construction d'un épais manteau neigeux. Le régime d'avalanches sur ce type de terrain réagit moins directement que les talus d'éboulis. Un synchronisme de courte durée serait également possible entre la chute des structures de glaces en amont des couloirs d'avalanches et des talus d'éboulis avec le déclenchement d'avalanche (Gauthier *et al.*, 2012; Graveline & Germain, 2016; B Hétu, 2007). Cette fenêtre de synchronisme serait d'environ deux semaines (Graveline & Germain, 2016).

Certains secteurs de la zone littorale réagissent différemment aux avalanches de neige. Une étude récente vise à développer des modèles de prévision des avalanches de neige pour le MTQ (Gauthier *et al.*, 2017). Cette étude a développé des modèles de régression logistique pour prédire la probabilité d'occurrence des avalanches de neige sur les routes 132 et 198. Des modèles ont été établis pour l'ensemble du secteur (70 km), mais également pour certains tronçons des routes 132 et 198 (Figure 2). Des modèles ont été établis pour les trois tronçons les plus problématiques : tronçon de Mont Saint-Pierre (100), Gros-Morne et Manche d'Épée (120-130) et la vallée de l'Anse Pleureuse (10) (Gauthier *et al.*, 2017). Ces modèles montrent différentes variables météorologiques statistiquement significatives entre les différents tronçons (Figure 2). Ces trois tronçons sont des talus d'éboulis actifs avec quelques différences géomorphologiques, mais leur position géographique (proximité de la mer et orientation des versants) pourrait expliquer les différentes variables météorologiques significatives.

A)

Location	Obs.	Variables	β	S.E	Wald Z	p-value	Nagelkerke R^2	Correct Prediction (%)
Route 132	N=1349	s2	0.216	0.012	18.000	<2E-3		
Section de route 100)	0=1247	r1	0.089	0.015	5.933	<2E-3	0.529	88.9
	1=102	dtr	-0.229	0.030	-7.633	<2E-3		
		Intercept	-1.689	0.186	-9.081	<2E-3		
Route 132	N=1435	s2	0.247	0.014	17.642	<2E-3		
(Section de route 120	0=1262	r1	0.101	0.016	6.313	<2E-3		
et 130)	1=173	windsp	0.032	0.004	8.000	<2E-3	0.621	89.3
		dtr	-0.200	0.033	-6.061	<2E-3		
		intercept	-3.624	0.351	-10.325	<2E-3		
Route 198	N=1355	s3	0.141	0.009	15.667	<2E-3		
(Section de route 10)	1=1272	r2	-0.401	0.136	-2.949	<2E-3	0.597	91.4
	0=83	dtr1	-0.331	0.044	-7.523	<2E-3		
		intercept	-1.313	0.249	-5.273	<2E-3		

B)

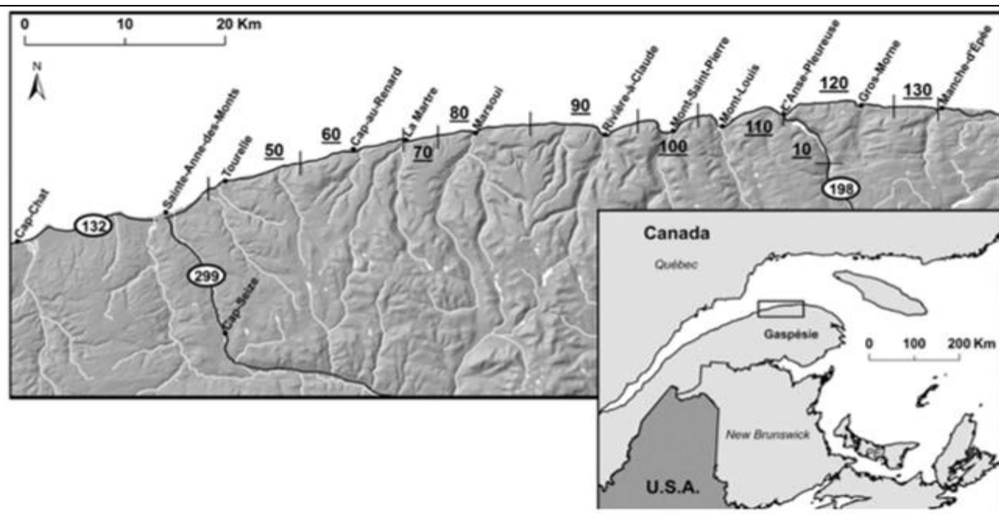


Figure 2. A) Modèle de régression logistique pour prédire la probabilité de déclenchement d'avalanche, tiré de Gauthier *et al.* (2017). Les variables s2 et s3 représentent la somme des précipitations solides sur 2 jours ou 3 jours (cm) ; r1 correspond à la somme des précipitations liquides sur 1 jour (mm) ; windsp correspond à la vitesse du vent (km/h) ; dtr et dtr1 correspondent à l'amplitude thermique journalière et une journée avant l'évènement. B) Carte de la localisation des routes et tronçons routier de la Péninsule gaspésienne (Gauthier *et al.*, 2017).

Le tronçon de L'Anse-Pleureuse semble réagir avec une journée de retard par rapport aux deux autres secteurs. Le tronçon de Manche d'Épée est influencé par la vitesse du vent, absent pour les deux autres secteurs. La différence entre les variables significatives pourrait être expliquée par l'orientation des versants (vent dominant/ radiation solaire) et leur proximité/exposition avec la mer. Ces facteurs explicatifs demeurent hypothétiques pour la région à l'étude puisqu'aucune étude ne documente la variabilité spatiale des conditions météorologiques, des propriétés de la neige et ultimement ces répercussions sur le régime d'avalanches. Cette variabilité spatiale représente une grande problématique pour la prévision des avalanches de neige pour ce secteur.

La littérature actuelle est entièrement composée d'approches empirico-statistiques pour le secteur à l'étude. Il serait intéressant d'avoir une approche méthodologique plutôt basée sur le processus et la modélisation pour valider les résultats émis par les approches empirico-statistiques. Pour utiliser une méthode basée sur les processus, différents types de données seraient nécessaires : des données décrivant les propriétés de la neige et les conditions météorologiques spécifiques à ces versants avalancheux.

Chic-Chocs

Ce secteur a été étudié dans le but de décrire son régime annuel d'avalanches (Boucher *et al.*, 2003; Germain *et al.*, 2009; Germain *et al.*, 2010). Les études réalisées pour ce secteur ont été faites à partir de la dendrochronologie. La résolution temporelle des études est annuelle, ce qui limite la comparaison entre les études du secteur côtier (résolution temporelle quotidienne et annuelle).

La morphologie des couloirs d'avalanches du massif des Chic-Chocs est différente du secteur côtier. Les couloirs d'avalanches du massif des Chic-Chocs sont plutôt des couloirs et des grandes cuves subalpines et alpines variant respectivement de 800 à 1100 m d'altitude et de 200 à 300m de dénivelé (Germain *et al.*, 2010). Cette morphologie et cette altitude permettent une accumulation de neige locale plus importante que sur la plupart des versants du secteur côtier. L'intervalle de retour des avalanches de neige est plus élevé que sur la côte variant de 2,3 à 10,5 ans avec une moyenne de 5,3 ans (Boucher *et al.*, 2003;

Germain *et al.*, 2009). Boucher *et al.* (2003) a étudié un couloir d'avalanche (Mont Hog's Back) et montre une relation entre une année à forte activité avalancheuse et des précipitations solides au-dessus de la moyenne climatique. L'étude de Germain *et al.* (2009) a étudié plusieurs couloirs d'avalanches répartis dans le massif des Chic-Chocs. Ces analyses font ressortir deux variables climatiques significatives responsables des fortes activités annuelles d'avalanches : 1) le nombre de jours où la température est positive et 2) le nombre d'évènements de pluie sur neige. Les analyses statistiques ont également mis en évidence cinq scénarios climatiques annuels: «well above-average total snowfall, high snowstorm frequency, major rain event and faceted-crust development, sequences of freezing rain and strong winds and early season of faceted-crust and depth-hoar» (Germain *et al.*, 2009).

Ces scénarios nous renseignent sur différents scénarios météorologiques décrivant le régime d'avalanches du massif des Chic-Chocs. L'influence des tempêtes hivernales est importante pour ce secteur. Le régime de fonte semble également influencé le déclenchement ainsi que sur la stratigraphie de la neige. Le rôle de la métamorphose de la neige est également mentionné comme étant un facteur pouvant expliquer les années à forte activité d'avalanches. Cependant, aucune étude ne présente des données à l'échelle journalière, ce qui limite la compréhension des facteurs de déclenchement d'avalanche. De plus, l'absence de données sur les propriétés du manteau neigeux spécifiques à la formation des avalanches (Schweizer *et al.*, 2003) limite la compréhension du régime d'avalanches propre aux Chic-Chocs.

Différence entre la côte et les Chic-Chocs

Un seul article a comparé le régime d'avalanches entre les deux secteurs (Germain *et al.*, 2010). Cet article n'a trouvé aucun synchronisme entre les années à forte activité d'avalanches du secteur côtier et celui des Chic-Chocs. Plusieurs facteurs géoclimatiques pourraient expliquer cette absence de synchronisme entre les deux secteurs. La différence d'altitude et de proximité avec la mer sont des facteurs qui pourraient influencer les conditions météorologiques et expliquer cette variation. De plus, le type de couloir d'avalanches ayant un impact sur le régime d'enneigement entre les deux secteurs est également très différent. Le secteur côtier est caractérisé par des talus d'éboulis côtiers ainsi que des couloirs forestiers à carapace de glace, contrairement aux cuves alpines et subalpines des Chic-Chocs. Aucune recherche ne s'est intéressée aux facteurs pour expliquer cette variation régionale, puisque la qualité et la quantité de données existantes sous représente les zones alpines et subalpines. La littérature actuelle est entièrement composée d’approches empirico-statistiques pour le secteur à l’étude. Il serait intéressant d’avoir une approche méthodologique plutôt basée sur le processus et la modélisation pour valider les résultats émis par les approches empirico-statistiques. Pour utiliser une méthode basée sur les processus, différents types de données seraient nécessaires : des données décrivant les propriétés de la neige et les conditions météorologiques spécifiques à ces versants avalancheux.

1.1.4 Variabilité spatiale des propriétés de la neige

Les avalanches de neige résultent d’une instabilité dans le manteau neigeux. Il existe deux types de déclenchement d’avalanche liés à des propriétés du manteau neigeux. Le déclenchement ponctuel est lié à une perte de cohésion entre les grains (e.g. McClung & Schaerer, 2006). Tandis que le déclenchement par plaque est lié à un système composé d’une couche faible surmonté d'une plaque cohésive. Trois éléments sont nécessaires à un déclenchement par plaque : le critère de rupture initial (Schweizer *et al.*, 2003), la taille critique de propagation (Gaume *et al.*, 2017) et le support de tension de la plaque (Reuter & Schweizer, 2018). L’analyse de ces éléments permet de déterminer la stabilité du manteau neigeux (Reuter & Schweizer, 2018). Cette analyse de stabilité est réalisée à partir des différentes propriétés du manteau neigeux, mesurées de manière quantitative et qualitative (Tableau 1).

Tableau 1. Nomenclature et unités de mesure des propriétés du manteau neigeux selon l'Association canadienne des Avalanches (CAA, 2014).

Type	Propriétés du manteau neigeux	Unité
Structurelle	Épaisseur des couches	cm
	Densité des couches	kg/m^3
	Taille des cristaux	mm
	Type de cristaux	classification
	Teneur en eau	ordinale ou %
Mécanique	Résistance à la pénétration	ordinale ou kPa
	Résistance à la compression	ordinale
	Capacité de propagation	ordinale ou %
Thermique	Gradient de température	°C/m

Les propriétés du manteau neigeux sont le résultat de la succession de plusieurs évènements météorologiques au courant de l'hiver (e.g. Schweizer *et al.*, 2003). L'interaction des variables météorologiques et la topographie font varier spatialement les propriétés du manteau neigeux. Cette variabilité spatiale influence l'occurrence spatiale et la taille probable d'une avalanche (Kronholm & Schweizer, 2003). Elle demeure la principale source d'incertitude en prévision des avalanches (Hägeli & McClung, 2004; Schweizer *et al.*, 2008). Cette incertitude est liée à l'extrapolation de données ponctuelles de stabilité. Cette extrapolation est faite quotidiennement par les prévisionnistes d'avalanche sur deux échelles spatiales, à l'échelle d'une pente (déplacement en montagne), du massif (bulletin d'avalanche) et régionale (chaîne de montagnes). L'échelle régionale est utilisée pour comparer différentes régions montagneuses, principalement au niveau climatique. L'échelle du massif est analysée lorsque la topographie varie en fonction de trois paramètres : altitude, angle de pente et orientation. L'échelle de la pente est analysée lorsque les trois paramètres topographiques ne varient pas ou peu, souvent sur une pente uniforme.

À l'échelle d'une chaîne de montagnes

À l'échelle régionale, les facteurs pouvant expliquer la variabilité spatiale des propriétés de la neige ont été discutés et validés dans la littérature. Différents contextes climatiques seraient responsables de la variation spatiale à grande échelle, à l'échelle des petites chaînes de montagne ou de régions montagnardes (Armstrong & Armstrong, 1987; Haegeli & McClung, 2007; Mock & Birkeland, 2000; Sturm *et al.*, 1995). À partir de classifications climatiques de régime d'avalanches de neige, une régionalisation de ces climats d'avalanches a été cartographiée pour en montrer la répartition spatiale. Des variables météorologiques spécifiques ainsi que des propriétés du manteau neigeux peuvent également être cartographiées (Figure 3).

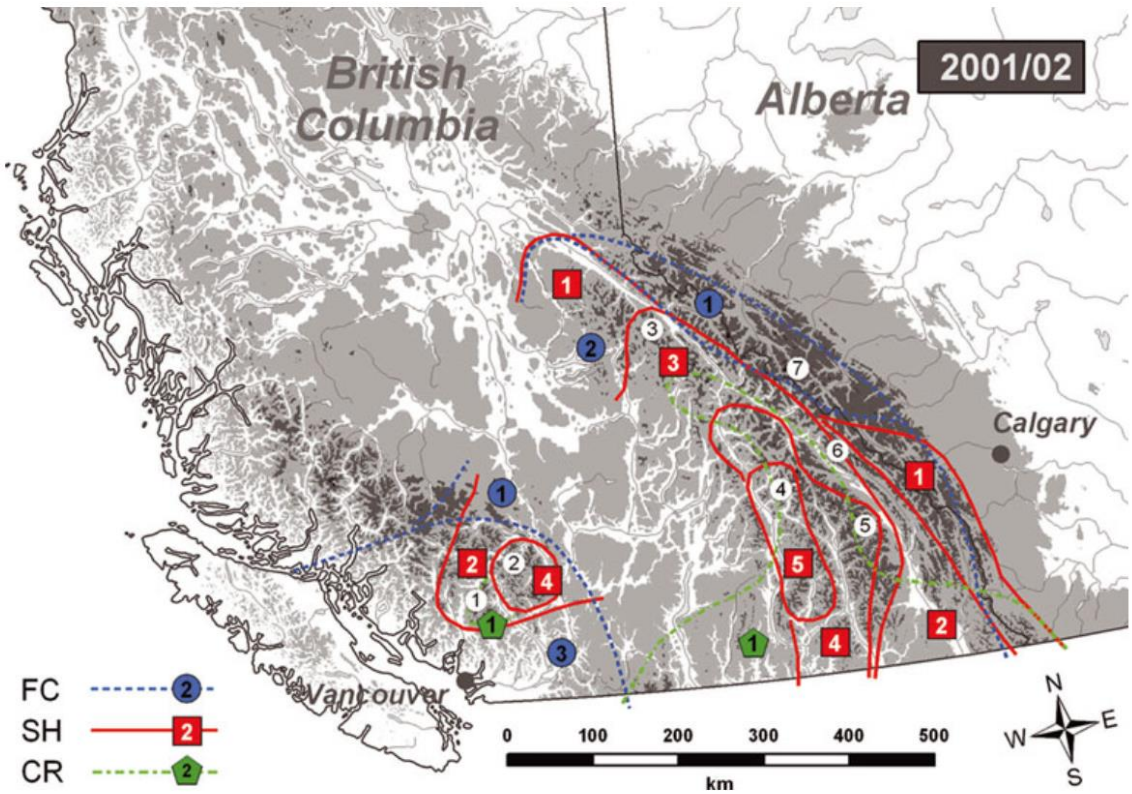


Figure 3. Cartographie des couches faibles persistantes dans l'Ouest canadien selon des profils idéalisés issus de la classification climatique d'avalanche et d'observations manuelles (Haegeli & McClung, 2007). Différentes couches faibles persistantes : couche de facette (FC), givre de surface (SH) et croûte de regel avec facette (CR). Les différents chiffres correspondent aux nombres de profils conceptualisés par secteur.

À l'échelle du massif

Les facteurs topographiques expliquent et prédisent spatialement les propriétés de la neige. Schweizer *et al.* (2008) mentionnent que la distribution spatiale des propriétés de la neige, plus précisément des couches faibles responsables de la formation d'avalanche, suit un «process-based terrain correlation», (Hägeli & McClung, 2003) reflétant une variation des processus météorologiques avec le terrain par exemple un régime de vent local dans une vallée (Feick *et al.*, 2007), des nuages de vallée (Colbeck & Jamieson, 2006) et le niveau de gel lors d'une tempête (Jamieson, 2006). Les facteurs topographiques pris en compte dans les analyses sont les suivants : l'angle de pente, l'orientation et l'altitude. Ces facteurs sont intéressants parce qu'un modèle d'élévation numérique peut facilement les générer. Des régressions linéaires et logistiques ont été utilisées pour expliquer ces variations à l'aide de variables exploratoires générées par des modèles d'élévation numériques et d'une variable indépendante (propriétés du manteau neigeux). Les variables indépendantes étudiées dépendent de l'objet d'étude, entre des variables quantitatives continues ou discrètes (Birkeland, 2001; Grunewald *et al.*, 2013; Reuter, van Herwijnen, *et al.*, 2015). La régression logistique a été utilisée avec la présence ou l'absence d'une couche de givre de surface ensevelie (Borish *et al.*, 2012; Schweizer & Kronholm, 2007) (Tableau 2). Le variogramme expérimental a également été utilisé pour décrire la structure spatiale de la présence d'une couche de givre de surface avec une distance d'autocorrélation variant de 500 à 1000 m, correspondant aux variations majeures de la topographie (vallée et versant) (Schweizer & Kronholm, 2007).

Tableau 2. Synthèse des travaux majeurs sur l'explication de la variabilité spatiale des propriétés de la neige par les facteurs topographiques, à l'échelle régionale

	Structurelle	**Mécanique**
Angle	Birkeland (2001) Schweizer & Kronholm (2007) Grunewald *et al.* (2013)	Birkeland (2001) Reuter, van Herwijnen, *et al.* (2015)
Orientation	Borish *et al.* (2012) Schweizer & Kronholm (2007) Grunewald *et al.* (2013)	Birkeland (2001) Reuter, van Herwijnen, *et al.* (2015)
Altitude	Jamieson (2006)	

Ces analyses ont permis d'identifier quels paramètres topographiques influencent quelles propriétés et comment ces propriétés varient dans l'espace. Par exemple, l'inclinaison de la pente et l'orientation des versants sont des paramètres topographiques pouvant expliquer la présence d'une couche de givre de surface (e.g. Schweizer & Kronholm, 2007) (Tableau 2). À partir de tests de stabilité faits sur l'ensemble d'un massif, Birkeland (2001) a montré que les versants nord sont généralement moins stables en hiver, puisqu'ils sont moins exposés au rayonnement soleil et donc plus sensible au développement de couche faible persistant. Avec le développement d'instruments et de modélisation, Reuter, van Herwijnen, *et al.* (2015) ont confirmé le fait que l'augmentation de l'angle de pente diminuait le critère de rupture initiale, mais pas la taille critique de propagation. Ils mentionnent également que l'orientation des versants est le facteur topographique le plus important pour décrire la distribution spatiale de la stabilité, incluant le critère de rupture initiale et la taille critique de propagation.

À l'échelle du versant

On distingue deux types de propriétés analysées dans l'ensemble de ces articles (Tableau 3). Les propriétés mécaniques de la neige représentent une grande proportion. Elles permettent d'analyser la stabilité d'un versant. Les propriétés structurelles permettent d’analyser de façon indirecte la stabilité d’une pente. L’analyse non spatiale intègre plusieurs observations de la même propriété pour en caractériser principalement la médiane et la variance, mais la position de ces observations n’est pas prise en compte dans l’analyse. Campbell & Jamieson (2007) ont montré la variabilité de résultats de test de stabilité en mettant perspective la médiane des résultats avec son coefficient de variation (dérivé de la variance). Ils ont mis en relation le coefficient de variation de la stabilité avec la variation de l’épaisseur de la plaque, montrant une faible stabilité pour les plaques moins épaisses dans un contexte de déclenchement par skieur seulement. La géostatistique prend en considération la position de chacune des observations pour estimer la variabilité spatiale sous forme d’un patron spatial à l’aide du variogramme. Cette méthode, basée sur l’analyse des variances entre individus statistiques et la distance qui les sépare, permet d’estimer la structure spatiale d’une variable à partir de trois paramètres : la distance d’autocorrélation, le *sill* et le *nugget*. Certains auteurs ont utilisé cette méthode pour décrire la variation de la stabilité à l’aide de ces trois paramètres (Kronholm & Schweizer, 2003; Reuter *et al.*, 2016). Kronholm & Schweizer (2003) ont combiné l’analyse non spatiale et la géostatistique pour décrire la variation de la stabilité à l’échelle d’une pente. Ils ont proposé un modèle conceptuel sinusoïdal pouvant décrire la stabilité selon différents scénarios de variabilité spatiale, basé sous trois paramètres : longueur d’autocorrélation, la médiane de la stabilité et la variation de la stabilité. Gaume *et al.* (2014) a obtenu les mêmes conclusions avec une analyse paramétrique basée sur un modèle numérique (éléments finis). Ces modèles, numériques et conceptuels, démontrent que la stabilité d’une pente diminue si la variance de la stabilité et la distance d’autocorrélation augmentent (Gaume *et al.*, 2014; Kronholm & Schweizer, 2003).

Tableau 3. Synthèse des travaux majeurs sur la variabilité spatiale des propriétés de la neige à l'échelle locale.

	Structurelle	Mécanique
Analyse non spatiale	Harper & Bradford (2003)	Campbell & Jamieson (2007) Eckerstorfer *et al.* (2014) Gaume *et al.* (2014) Kronholm & Schweizer (2003)
Géostatistique	Bellaire & Schweizer (2011) Feick *et al.* (2007) Lutz & Birkeland (2011)	Kronholm & Schweizer (2003) Reuter *et al.* (2016)

Pour expliquer la variabilité spatiale des propriétés à l'échelle d'une pente, l'influence des processus microméteorologiques sur le couvert neigeux est discutée par plusieurs auteurs (Campbell & Jamieson, 2007; Harper & Bradford, 2003; Kronholm & Schweizer, 2003; Lutz & Birkeland, 2011; Reuter *et al.*, 2016; Schweizer *et al.*, 2008). Ces processus microméteorologiques font référence, par exemple, aux formes d'ondulation dans la neige exposée au vent (Campbell & Jamieson, 2007) ou à l'influence de la radiation solaire sur la surface neigeuse dans un environnement forestier (Lutz & Birkeland, 2011). À l'aide d'une méthode géostatistique, une récente étude a exclu l'hypothèse que seulement les facteurs topographiques pouvaient être responsables de la variabilité (Reuter *et al.*, 2016). Les distances d'autocorrélation issues de différents articles estimaient une distance d'autocorrélation d'environ 10 m. Cette distance décrit un phénomène qui varie à petite échelle. L'étude de Reuter *et al.* (2016) a la même méthodologie avec une taille de support de 500m, beaucoup plus grande que ceux recensés dans la littérature (Tableau 4). Les distances d'autocorrélation variaient de 5 à 31m alors que la topographie varie selon une distance d'autocorrélation de 47 à 102m. (Reuter *et al.*, 2016). Cependant, la variation de la microtopographie (convexité/concavité) n'est pas incluse dans la modélisation spatiale et pourrait expliquer une partie de la variation.

Tableau 4. Synthèse des différentes distances d’autocorrélation obtenues à partir de la méthode du variogramme, en fonction de différentes tailles de support d’échantillonnage (Reuter *et al.*, 2016).

	Distance d’autocorrélation (m)	**Taille du support (m)**
Bellaire & Schweizer (2011)	2 à 8m	19
Schweizer & Reuter (2015)	2 à 8 m	19
Lutz *et al.* (2007)	1 à 13 m	23
Reuter *et al.* (2016)	5 à 31 m	500

Le rôle de l’interaction entre la microtopographie (forme et rugosité du terrain, présence de végétation/roche) et les processus météorologiques est souvent mentionné comme étant l’explication possible de la variation spatiale de plusieurs propriétés du manteau neigeux (e.g. Guy & Birkeland, 2013; Reuter *et al.*, 2016). Des études ont montré l’influence de la microtopographie sur la variation spatiale de l’épaisseur du manteau neigeux (Deems *et al.*, 2006; Elder *et al.*, 1991; Mott *et al.*, 2010; Trujillo *et al.*, 2007, 2009; Winstral *et al.*, 2002). Les jeux de données spatiales de hauteur de la neige ont principalement été acquis par LiDAR aéroporté en hiver, mais également en été pour caractériser la microtopographie, ce qui facilite la couverture spatiale et la densité de point de mesure pour faire ce type d’analyse portant sur la microtopographie. Ces études ont inclus la hauteur de la neige, mais aucune n’a utilisé des données de propriétés du manteau neigeux, qui requiert un échantillonnage plus complexe sur le plan de la logistique et de l'instrumentation.

1.2 PROBLÉMATIQUE

Les Chic-Chocs et la côte nord de la péninsule gaspésienne sont menacés par le risque d’avalanche de neige. Au total, trois accidents mortels sont survenus dans les Chic-Chocs et ceux-ci sont fréquentés par des usagers de l’arrière-pays (ski, planche à neige et raquette), de plus en plus présent au fil des années. Cette fréquentation exponentielle laisse présager une augmentation des accidents dans les Chic-Chocs (Boucher & Hétu, 2009). Avalanche Québec est un organisme à but non lucratif œuvrant dans le domaine de la sécurité en avalanche depuis 2000. L'organisme émet un bulletin de neige aux 2 jours pour les Chic-Chocs, décrivant le risque d'avalanche. L'expertise de ce groupe ainsi que son fonctionnement opérationnel sont fortement influencés par les standards de l'industrie canadienne, notamment par l'Association canadienne des avalanches. Ces standards ont été développés dans différents climats de neige de l'Ouest canadien et ne représentent pas la réalité climatique des Chic-Chocs. De plus, Avalanche Québec a développé son expertise avec plus de 15 ans d'expérience dans le climat et terrain des Chic-Chocs. L'organisme possède des données de prévision (type de problèmes d'avalanche) qui pourraient être intégrées dans une étude approfondie sur le climat de neige avec différents types de données.

Depuis 2006, environ 500 avalanches de neige ont atteint les routes de la côte nord de la péninsule gaspésienne, totalisant 11 accidents avec des voitures (Gauthier *et al.*, 2017). De plus, trois accidents mortels sur ces routes ont également marqué la région dans les années 1900 (Boucher & Hétu, 2009). Depuis 2016, Avalanche Québec émet une prévision du risque d'avalanche journalier pour le MTQ. Ce bulletin couvre les couloirs d'avalanches bordant la route 132 et 198 de Ruisseau-Castor à Manche d'Épée, sur la côte nord de la péninsule gaspésienne. L'expertise d'Avalanche Québec est basée sur des connaissances principalement établies dans l'Ouest canadien et également d'expérience de prévision des avalanches dans les Chic-Chocs. Le climat et le régime d'avalanches diffèrent grandement entre les Chic-Chocs et la côte nord de la péninsule gaspésienne. Une comparaison climatique entre ces deux secteurs de prévision des avalanches Québec pourrait faciliter l'adaptation de l'équipe de prévision pour ce récent secteur de prévision des avalanches. De plus, le bulletin d'avalanche pour ce secteur est divisé en deux sous-secteurs, les versants adjacents à la route provinciale 132 qui font face à la mer et ceux à l'intérieur de la vallée de L'Anse-Pleureuse, adjacents à la route provinciale 198. Cette séparation entre la côte (132) et la vallée (198) a été remarquée lors de l'étude de Gauthier *et al.* (2017), mais également constaté par les prévisionnistes lors de la première année de prévision des avalanches dans ce secteur. Il est nécessaire d'étudier la variabilité des processus météorologiques, des propriétés du manteau neigeux et ultimement du régime d'avalanches entre les versants côtiers et ceux situés en vallée. Une analyse à l'échelle du versant serait également pertinente pour mieux connaître les patrons d'accumulation de neige et de possibles zones faibles sur le versant. Cela pourrait permettre une meilleure efficacité d'un système de prévention et d'un futur système d'atténuation des avalanches (contrôle par explosifs et clôtures à neige par exemple).

Les couloirs le long de la côte ont été sujets à de nombreuses études portant sur les régimes d'avalanches notamment celle de Gauthier *et al.* (2017), mais aucune n'a intégré les propriétés de la neige qui constituent l'indicateur principal de la formation d'avalanche (Schweizer *et al.*, 2003). Une étude qui intègre ce type de données est donc nécessaire pour valider les modèles de prévisions d'avalanches développés par Gauthier *et al.* (2017). Ces modèles, lorsqu'ils seront validés par des données sur le manteau neigeux, pourront être utilisés comme outils par les prévisionnistes d'avalanche et les gestionnaires routiers.

1.3 OBJECTIFS

Le présent projet vise à documenter la variabilité spatiotemporelle des propriétés du manteau neigeux pour les deux secteurs de prévision d'Avalanche Québec. La variabilité spatiotemporelle sera d'abord décrite à l'échelle de plusieurs saisons hivernales pour les deux secteurs de prévision d'Avalanche Québec entre les Chic-Chocs et la côte nord de la péninsule gaspésienne. Ensuite, la variabilité spatiotemporelle sera analysée à l'intérieur d'une saison hivernale entre deux versants qui bordent les routes provinciales 132 et 198, ainsi qu'à l'échelle de chacun des versants (Figure 2-B). La réalisation de l'objectif principal du projet repose sur les cinq objectifs spécifiques suivants :

1) Décrire le climat de neige et d'avalanches pour la péninsule gaspésienne.

2) Analyser la variabilité spatiale entre les données météorologiques et de propriétés du manteau neigeux entre un versant côtier (132) et un situé en vallée (198).

3) Estimer la variabilité spatiale de l'accumulation de neige pour chacun des versants à l'étude en utilisant la géostatistique avec une attention particulière à la distribution de la végétation.

CHAPITRE 2
LE CLIMAT DE NEIGE TRANSITION «RAINY CONTINENTAL» DE LA PÉNINSULE GASPÉSIENNE

Résumé en français du premier article

Les climats de neige font l'objet d'études scientifiques depuis de nombreuses décennies, puisqu'ils sont la base d'un programme de prévision opérationnelle d'avalanche. Des études récentes ont également ajouté de nouveaux climats de neige à ceux déjà établis dans l'Ouest américain recensés dans la littérature (continentale/maritime/transition). La péninsule gaspésienne, située dans l'est du Canada, est caractérisée par deux régions menacées par les avalanches de neige : le massif intérieur des Chic-Chocs et les pentes côtières situées au nord de la péninsule. Pour caractériser ces deux régions, nous avons intégré dans notre analyse plusieurs types de données issues de méthodes éprouvées : des données météorologiques, des profils de neige et des types de problèmes d'avalanches (données de prévision des avalanches). L'analyse des données météorologiques suggère des hivers continentaux et maritimes. Les données de profil de neige révèlent un manteau neigeux froid et mince avec majoritairement des cristaux à face plane et des croûtes de regel. La présence/absence de type de problème persistant d'avalanches varie entre les hivers, et est moins importante que dans un climat continental de l'Ouest canadien. Nous avons comparé nos résultats avec le Mont Washington et les Alpes centrales japonaises et suggérons d'adopter le terme *rainy continental* comme climat de neige de type transition pour la péninsule gaspésienne. Nous proposons également un nouveau modèle conceptuel plus intégrateur pour classifier les climats de neige.

Ce premier article, intitulé « *The northeastern Rainy Continental snow-climate: A Transitional snow climate for the Gaspé Peninsula, Québec, Canada*», fut rédigé par moi-même en tant que premier auteur. Mon directeur Francis Gauthier, mon co-directeur Alexandre Langlois et le directeur d'Avalanche Québec, Dominic Boucher, m'ont accompagné dans le processus intellectuel et dans la révision de l'écriture de cet article. Une version préliminaire des résultats a été présentée sur une affiche scientifique au *International Snow Science Workshop* (ISSW) à Innsbruck, à l'automne 2018. Cette version étendue sera soumise pour l'édition spéciale du ISSW dans la revue *Cold Regions Science and Technology* à l'hiver 2019.

The northeastern Appalachian Rainy Continental snow climate: A Transitional snow climate for the Gaspé Peninsula, Québec, Canada

2.1 INTRODUCTION

Snow-climate classifications were developed to characterize mountain range climate in the study of avalanche hazards (Armstrong & Armstrong, 1987; LaChapelle, 1965; McClung & Schaerer, 2006; Mock & Birkeland, 2000). In hydrology and climate modelling, the term snow-climate has been used to describe seasonal average snowpack properties such as total depth, percentage of depth hoar, ice layers and snow temperature (Sturm *et al.*, 1995). In the study of snow avalanches, the term snow-climate refers to snowpack properties specifically relevant to snow avalanche formation (Hägeli & McClung, 2003)The snow-climate classification of a given mountainous region is crucial to developing a location-specific avalanche mitigation and forecasting program (e.g. McClung & Schaerer, 2006). Three main snow-climates are listed in the literature: Maritime, Continental and Transitional (LaChapelle, 1965). The Maritime snow-climate is characterized by warm temperatures and heavy snowfall. Major instabilities are mostly caused by recent snow loading in the upper snowpack (Haegeli & McClung, 2007; Mock & Birkeland, 2000). Forecasting programs in these mountain ranges rely mostly on weather observations (McClung & Schaerer, 2006). The Continental snow-climate has cold temperatures and light snowfall. The snowpack has weak persistent layers that require systematic monitoring in order to forecast snow avalanche occurrence (McClung & Schaerer, 2006). The Transitional snow-climate experiences both Maritime and Continental snow-climate characteristics (Haegeli & McClung, 2007). However, transitional snow-climate description is general and was strictly described in western North America (Hägeli & McClung, 2003), but other areas experience different continental and maritime influence should be described enriching this Transitional snow-climate (Haegeli & McClung, 2007).

Mock & Birkeland (2000) proposed a flowchart to classify snow-climate, describing snowpack processes relevant to avalanche hazard. They used meteorological data as input to classify individual winter seasons into snow-climates. However, Schweizer *et al.* (2003) demonstrated that slab and weak layer physical properties are key indicators of avalanche formation (Hägeli & McClung, 2003). Haegeli & McClung (2007) indicated the need for other types of snow stratigraphy information to improve snow-climates description. They proposed expanding the Mock & Birkeland (2000) flowchart to include avalanche and snowpack observations, particularly persistent weak layer observations, leading to the term *snow and avalanche climate* (Haegeli & McClung, 2007). Their inclusion gives more information on the percentage of avalanche activity on persistent weak layers and the types of persistent weak layers that characterize each snow and avalanche climate zone. This is relevant to specify Transitional snow-climate where both Continental and Maritime influence led to specific main persistent weakness that prevents in a particular area. More recently, Statham *et al.* (2018) developed a conceptual model of avalanche hazard. This conceptual model uses several components to describe the avalanche hazard and was developed specifically to focus on avalanche risk management. The principal component is the avalanche problem type (Statham *et al.*, 2018), which refers to specific weather events and snowpack properties that describe the character of the avalanche problem type, such as wind slab or persistent slab avalanche problem type. These avalanche problem types are the main concern of the avalanche forecaster regarding specific meteorological and snowpack conditions. Each avalanche problem type has specific risk mitigation strategies, and this conceptual model is used in several avalanche operational hazard forecasting and training programs (Statham *et al.*, 2018). Shandro & Haegeli (2018) used forecasted avalanche problem data and the Mock & Birkeland (2000) flowchart for a better characterization of snow avalanche hazard in western Canada. As the Mock & Birkeland (2000) methodology provided general description of the snow climate throughout several winters seasons, the addition of avalanche problem type data provided an in-depth look for daily concern for forecasters during the season.

Combinations of the methodologies mentioned above have been used to describe and classify additional regions, using different data types based mainly on data availability. Ikeda *et al.* (2009) described the snow-climate of the Japanese Alps using the Mock & Birkeland (2000) flowchart and snowpack data. Their results for the Japanese Coastal mountains showed similarities with the Maritime climate zone. However, they found that the Central Japanese Alps, characterized by thin snowpack, cold temperatures for persistent weakness development and a significant amount of rainfall, did not correspond to any of the three main snow-climates. Thus they proposed the term "Rainy Continental" for the Central Japanese Alps (Ikeda *et al.*, 2009). Eckerstorfer & Christiansen (2011) used snow profile data to describe the snow-climate of Svalbard's main settlement, Longyearbyen. They focused on snowpack properties, as they are key indicators of snow avalanche formation. Their results indicated a thin snowpack, persistent weakness and a significant amount of ice layering due to a maritime influence. They proposed the term "High Arctic Maritime" for Central Svalbard (Eckerstorfer & Christiansen, 2011).

Two regions of the Gaspé Peninsula in eastern Canada are snow avalanche-prone: the Chic-Chocs mountain range, which is popular for recreational backcountry activities, and the north shore of the peninsula, where the road network is threatened (Figure 1). Multiple studies have shown the influence of snow storms and thaw events on the local snow avalanche regime (refers to avalanche events) (Fortin *et al.*, 2011; Gauthier *et al.*, 2017; Germain *et al.*, 2009; B Hétu, 2007). While the Köppen classification is humid continental, the region's climate has a significant maritime influence (Fortin *et al.*, 2011; Gagnon, 1970; Gauthier *et al.*, 2017). This contrast makes snow and avalanche climate classification difficult for the peninsula. Although the winter climate of the region has been well-documented by many authors (Fortin & Hétu, 2013; Fortin *et al.*, 2011; Gagnon, 1970; Gauthier *et al.*, 2017), it relies on seasonal average climate conditions not relevant to avalanche formation. Thus, snowpack evidence and meteorological data relevant to avalanche formation are needed to fully explain the region's snow and avalanche climate. Given the presence of three proven approach in snow climatology and the importance of fully understanding the snow and avalanche climate of the Gaspé Peninsula, this paper has two main objectives: 1) Describe the snow-climate for the Gaspé Peninsula; 2) Compare the three approaches to describe snow-climate type. We then compare our results of snow-climate studies with other snow-climate areas. We conclude our paper with discussing the implications of the new climate type for avalanche safety programs."

2.1.1 Study Area

This study is centred on the Gaspé Peninsula, located in the northern portion of the Appalachian Mountains, which extend southwestward along the east Gaspé North Coast of North America to Alabama (Figure 4). We focus on two main study areas: the Chic-Chocs mountain range and the peninsula's north shore. The Chic-Chocs range—a northern expression of the Appalachian Mountains—is an inland massif that forms the spine of the peninsula (Figure 4). This central massif is subalpine and alpine, between 800 to 1200 m a.s.l., and is surrounded by a lower plateau at 400-500 m a.s.l. (Figure 4 a-b). The second study area, on the peninsula's north shore, consists of the slopes along provincial road 132 between Sainte-Anne-des-Monts and Rivière-la-Madeleine and along provincial road 198 at l'Anse Pleureuse (Figure 4). These avalanche slopes are at low elevation (from 0 to 200 m a.s.l.) and have vertical relief from 40 m to 200 m. Vegetation is sparse along the avalanche path (Figure 4 c-d). Both study areas are in the Avalanche Québec forecasting area. This non-profit organization has issued biweekly avalanche bulletins for the backcountry users of the Chic-Chocs since 2000. It has also published a daily avalanche hazard bulletin for provincial roads 132 and 198 since 2016 (Québec Ministry of Transports) (Figure 4).

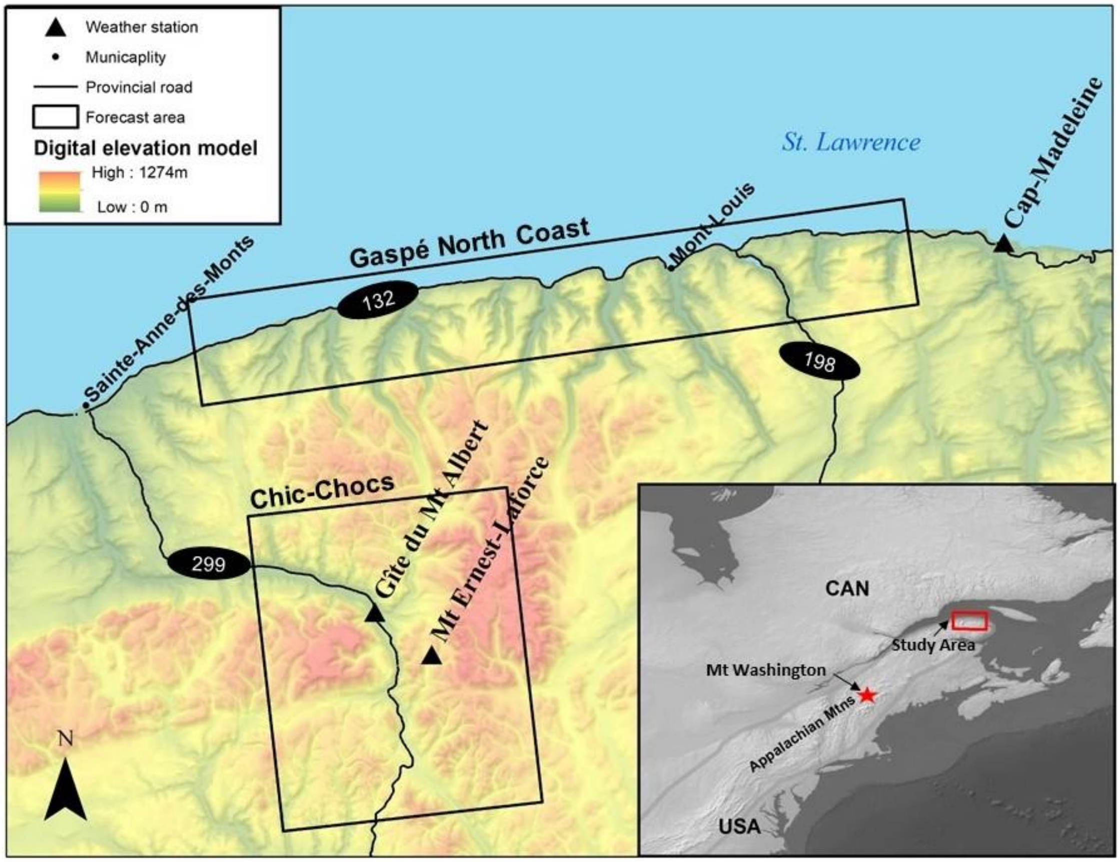


Figure 4 Study area map, showing the two Avalanche Québec forecast areas and weather stations (Cap-Madeleine (29 m), Gîte du Mt Albert (253 m) and Mt Ernest-Laforce (630 m)).

The region receives 800 mm of precipitation annually in the Gaspé North Coastal area and around 1,600 mm on the high plateau of the interior (Fortin *et al.*, 2011; Gagnon, 1970; Germain *et al.*, 2010). Snow typically falls from December to April, along with about 60 mm of rainfall per winter (Fortin *et al.*, 2011). The mean annual temperature for the period 1971-2010, ranges from 3°C along the Gaspé North Coast (Environment Canada, 2010) to -4°C in the Chic-Chocs (Gray *et al.*, 2017). The regional climate is characterized by contrasting weather patterns: 1) cold Artic air masses usually bring northwestern wind with temperatures below -20°C and 2) continental low-pressure systems, typically with northeastern winds, warm temperatures near the freezing point and precipitation. These storms are commonly known as the Alberta Clipper, the Colorado Low and the Hatteras Low (Fortin & Hétu, 2013). Their trajectories over the Gaspé Peninsula can bring temperatures above or below the freezing point, thus affecting the type of precipitation (Fortin & Hétu, 2013). The wind regime combines with topographic features specific to both study areas to create a snow accumulation pattern that is prone to avalanche formation (Germain *et al.*, 2010). Most avalanche in this region are direct action avalanches that occur during storms. (Fortin *et al.*, 2011; Gauthier *et al.*, 2017; Germain *et al.*, 2009; B Hétu, 2007). There seems to have considerable difference when comparing annual snow avalanche regime between the low-coastal scree slope and the Chic-Chocs (Germain *et al.*, 2010). These results suggest the influence of local effect on the snow avalanche regime (Germain *et al.*, 2010). The results for both study areas in the present study are expected to indicate the need for one or two snow and avalanche climates.

2.2 DATA AND METHODS

2.2.1 Classification strategy

To describe the snow and avalanche climate in a more inclusive way, we used three methodologies from different studies focusing on snow and avalanche climatology of the past decades (Mock & Birkeland, 2000; Shandro & Haegeli, 2018; Sturm *et al.*, 1995). We used these methodologies as a base for our methodology and we didn't take into account all aspects of these methodologies. However, this methodology included multiple types of data relevant to avalanche formation. First, we used the Mock & Birkeland (2000) flowchart to describe the general snow-climate with meteorological data (Figure 5, Table 5-B). Then we used snow profile observations to characterize the snow grain type distribution, as a part of Sturm *et al.* (1995). A prevalence of a low or high temperature gradient snow grain type gives information about the dominant metamorphism process, such as faceting or rounding (e.g. Madore *et al.*, 2018). This snowpack data identifies the dominant metamorphism process and can be used to better explain the snow-climate classification results (Figure 5). Lastly, we used forecasted avalanche problem types to describe specific avalanche hazard (Shandro & Haegeli, 2018). Avalanche problem types are issued every day by avalanche technicians and forecasters using specific terminology from Statham *et al.* (2018) to provide information on the type of snow instability during the period covered by the bulletin. Produced by professional avalanche forecasters based on an analysis of weather and snow profile observations, they represent a reliable proxy to analyze the avalanche hazard and including this information in the snow and avalanche climate description (Figure 5). We will also perform Wilcoxon-rank sum test to explore differences between study site for the different method. Finally, we will discuss the outcome of different data and methods used in this study and highlight the benefit of using multiple types of data. The database for all types of data represents the winter avalanche regime from December 1 to March 31. The spring avalanche regime is not considered in this study.

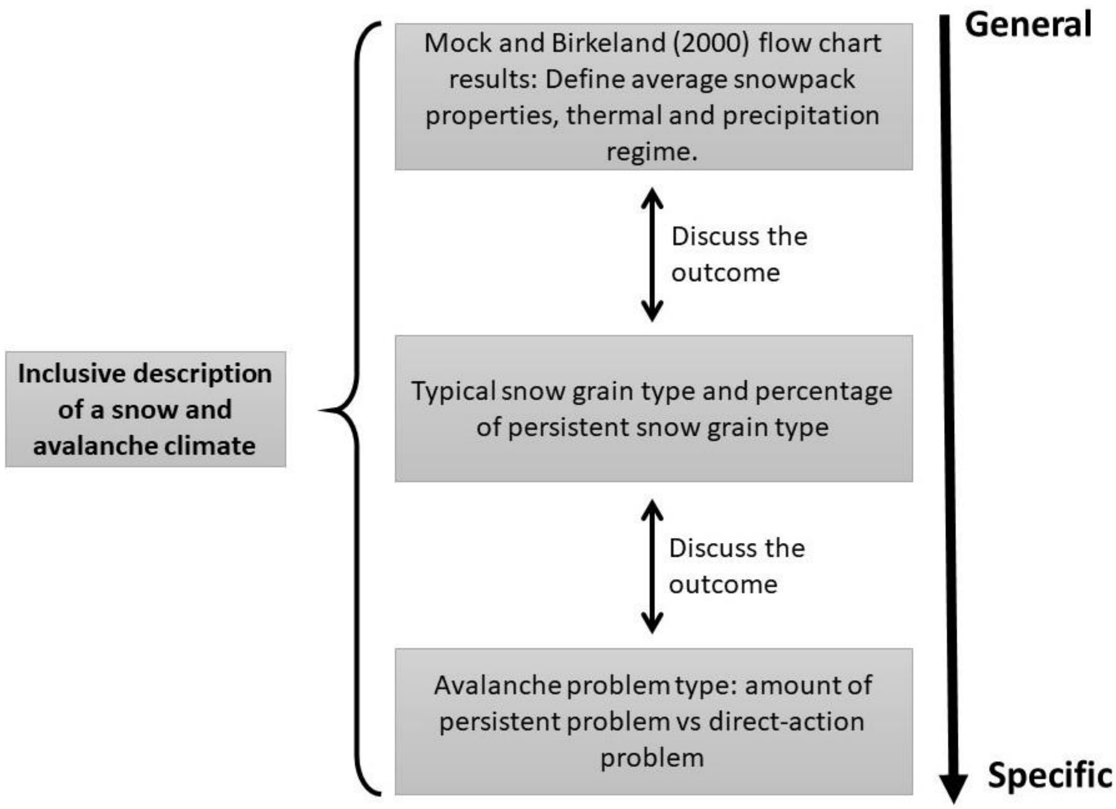


Figure 5. Snow and avalanche climate description following our procedure to discuss the different outcomes from different types of data used. Direct-action avalanche problem refers to all the others avalanche problem types expect persistent avalanche problem type.

2.2.2 Meteorological data and classification

Meteorological data was provided by various organizations: Avalanche Québec, the Québec Ministry of Environment and Climate Change, and Environment Canada. Data for the Chic-Chocs range came from the Gîte du Mt Albert weather station located at 253 m a.s.l (valley floor) and from the Ernest-Laforce weather station located on the north slope of Mt Ernest-Laforce at 630 m a.s.l (Figure 4). Data for the Gaspé North Coast came from the Cap-Madeleine weather station at 29 m a.s.l (Figure 4). The dataset covers the winter season (December to March) from 2012-2013 to 2017-2018 (Table 5). Mock & Birkeland (2000) did not include the month of April in their methodology. Hourly data for air mean temperature, snow height and precipitation (weighing precipitation gauge) data was used to calculate the meteorological variables needed for the Mock & Birkeland (2000) flowchart: daily mean air temperature (°C), total snowfall (cm), total rainfall (mm), total snow water equivalent (mm) and mean December temperature gradient (°C/m) (Table 5-b). Rainfall and snow water equivalent (SWE) were derived from the total precipitation, using a threshold of 0°C with the hourly mean air temperature. To minimize the misclassification of precipitation events that could lead to a snow-climate misclassification, snow events were validated by the presence of a significant increase (>2 cm) in snow height, within the next two hours following the precipitation event. Rain events were validated according to the same procedure, if the snow height was stable or decreasing (0cm or -1cm). Snow height was measured every hour with an ultrasound snow depth sensor (SR50 from Campbell Scientific) on an automated weather station. Some weather stations had significant exposure to the wind, while others, located in forested area, had more protection. This led to the over- or under-estimation of snowfall in different locations. In order to standardize snowfall measurements, we decided to use the snow water equivalent data in mm with a 1:10 ratio to calculate the snowfall in cm (Ikeda *et al.*, 2009). Mean December temperature gradient was found with the mean air December temperature and the mean December snow height, assuming zero°C at the snow-soil interface (Mock & Birkeland, 2000).In order to compare our data with a potentially similar location in the Appalachian Mountains, we used data from the Hermit Lake Snow

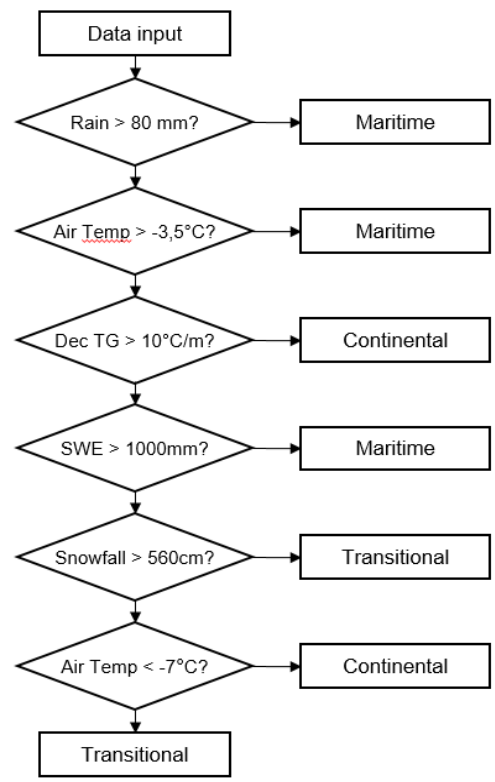
Plot (1180 m a.s.l.) on Mt Washington, USA (Figure 4). This data was provided by the Mt Washington Avalanche Center for winters 2012-2013 to 2017-2018.

Table 5. A) Summary of data for the two study area over time. B) Flow chart methodology of Mock & Birkeland (2000).

A)

Season	Gaspé North Coast		
	Weather data	Snowprofile	Avanche problem type data
2012-2013	X		
2013-2014	X		
2014-2015	X	X	
2015-2016	X	X	
2016-2017	X	X	X
2017-2018	X	X	X
	Chic-Chocs		
Season	Weather data	Snowprofile	Avanche problem type data
2012-2013	X		X
2013-2014	X		X
2014-2015	X	X	X
2015-2016	X	X	X
2016-2017	X	X	X
2017-2018	X	X	X

B)



2.2.3 Snow grain type dataset

Snow profiles in the Chic-Chocs range were carried out by Avalanche Québec technicians from December to March (Table 5). They were dug every week of the winter season at locations with different slopes and elevations within the forecast area. Approximately 10 to 20 snow profiles were dug at each study site per winter season. Since avalanche forecasting for the Gaspé North Coastal area only started in winter 2016-2017, fewer snow profiles have been performed each winter by researchers (Table 5).

Approximately 12 snow profiles were performed per winter in the Gaspé North Coast area, except during the 2015-2016 season, when only three snow profiles were obtained. Snow grain type in each layer was classified according to the *Observational guidelines and recording standards for weather, snowpack and avalanche* from the Canadian Avalanche Association (CAA, 2014). Snow grain type distribution was derived from the thickness and number of layers of each grain type. The probability of finding a certain grain type was divided by the sum of the thickness of all layers with the same grain type to give the probability by centimeter (%/cm). Snow grain type distribution was calculated for each winter in both study areas.

2.2.4 Avalanche problem type dataset

Over the operational winter, daily avalanche problem types for each study area were issued by the avalanche forecaster and technician. Shandro & Haegeli (2018) included the avalanche problem concept in their methodology with all the hazards dimension such as avalanche problem type, likelihood of avalanches, destructive size, danger rating and elevation band (Statham *et al.*, 2018). We focus on a more simplified approach using the frequency of each avalanche problem type for each winter and the average over all winters. We computed these frequencies over the sum of all avalanche problem type used during a season, including days when more than one avalanche problem type was used and when no avalanche problem type was used (counting as one no avalanche problem). Anomalies were computed with the difference from the average for every avalanche problem type. The dataset covers six winters, from 2012-2013 to 2017-2018, for the Chic-Chocs range and two seasons, from 2016-2017 to 2017-2018, for the Gaspé North Coast (new forecast area since 2016). Winter 2016-2017 and 2017-2018 data for the two study areas was compared to determine the spatial variability of snow avalanche problem types.

2.3 RESULTS

2.3.1 Snow-climate classification

Snow-climate classification results from the Mock & Birkeland (2000) flowchart indicated a Continental climate (4/6 winters) with a Maritime exception (2/6 winters) (Table 6). Both the Gaspé North Coast and the Chic-Chocs study areas were characterized mostly by cold temperature (<-7°C) and small amounts of precipitation (<450 mm SWE). The decisive criterion that classified most of the winter seasons is the mean December temperature gradient above 10°C/m (Continental) and the rainfall above 8 cm (Maritime) (Table 6). Snow accumulation classification criteria for the Maritime and Transitional snow-climates were never used during the classification. The average air temperature (<-7°C) and December temperature gradient (>10°C/m) for every weather station were below (air temperature) or over (temperature gradient) the threshold for Continental classification (Table 6). The combination of cold mean air temperature and thin snow cover could explain the high value of temperature gradient for every weather station, particularly for the Cap-Madeleine weather station (Table 6). Cold air temperature and shallow snowpack in December are key drivers to facet metamorphism (e.g. Mock & Birkeland, 2000). Winters 2012-2013 and 2015-2016 were warmer at every weather station, resulting in more rain events during the winter season (Table 6). These winters were classified as Maritime winters with rainfall exceeding 80 mm. We observed the same classification pattern for the two weather stations in the Chic-Chocs area and presented only one of them. Despite similar classification between all weather stations, most of the meteorological variables were significantly different using the Wilcoxon-rank sum test: air temperature (w=36, p-value < 0.05), SWE (w=0, p-value<0.05), Dec_TG (w=25, p-value <0.05) and snow height (w=0, p-value<0.05). Rainfall was not significantly different (w=11, p-value>0.05). Table 6 shows warmer conditions in the Gaspé North Coast area with an average temperature of -7°C at Cap-Madeleine (Gaspé North Coast) and -11.48°C at Mt Ernest-Laforce (Chic-Chocs).

Table 6. Snow-climate Classification results for winters 2012-2013 to 2017-2018. HS: Snow height maximum. SWE: Snow water equivalent. Dec_TG: mean December temperature gradient.

	Air temp (°C)	HS (cm)	Snowfall (cm)	SWE (mm)	Rainfall (mm)	Dec_TG (°C/m)	Snowclimate	Decisive criterion
Cap-Madeleine (29m) Gaspé North Coast								
2012-2013	-5.48	32.00	234.60	234.60	146.90	62.40	Maritime	rain >8cm
2013-2014	-9.29	N/A	194.80	194.80	0.40	N/A	Continental	moytemp < -7°C
2014-2015	-8.89	6.00	185.40	185.40	33.90	55.41	Continental	dec TG > 10°C/m
2015-2016	-5.19	2.00	126.50	126.50	81.00	59.97	Maritime	rain >8cm
2016-2017	-6.56	20.00	226.00	226.00	20.70	103.10	Continental	dec TG > 10°C/m
2017-2018	-6.67	22.00	243.30	243.30	13.80	72.88	Continental	dec TG > 10°C/m
Average	-7.01	16.40	201.77	201.77	49.45	70.75	Continental	dec TG > 10°C/m
Mt Ernest-Laforce (630m) Chic-Chocs								
2012-2013	-9.72	112.00	466.20	466.20	91.00	15.59	Maritime	rain >8cm
2013-2014	-13.89	109.00	457.10	457.10	23.30	23.95	Continental	dec TG > 10°C/m
2014-2015	-13.69	117.00	401.60	401.60	72.80	13.22	Continental	dec TG > 10°C/m
2015-2016	-9.50	N/A	358.10	358.10	103.50	N/A	Maritime	rain >8cm
2016-2017	-11.71	113.00	454.00	454.00	37.60	20.10	Continental	dec TG > 10°C/m
2017-2018	-10.39	132.00	405.60	405.60	50.70	17.78	Continental	dec TG > 10°C/m
Average	-11.48	116.60	423.77	423.77	63.15	18.13	Continental	dec TG > 10°C/m
Hermit lake (1180m) Mt Washington								
2012-2013	-8.82	103.35	489.30	384.65	103.10	17.44	Maritime	rain>8cm
2013-2014	-11.07	65.17	458.45	296.50	102.20	21.39	Maritime	rain>8cm
2014-2015	-11.57	113.00	377.02	309.20	29.60	7.09	Continental	temp<-7°C
2015-2016	-6.43	55.04	213.85	167.90	178.30	14.69	Maritime	rain>8cm
2016-2017	-9.10	162.64	297.40	255.45	25.00	6.32	Continental	temp<-7°C
2017-2018	-9.72	112.49	422.23	368.80	130.00	16.09	Maritime	rain>8cm
Average	-9.45	101.95	376.38	297.08	94.70	13.84	Maritime	rain>8cm

* Mean december snow depth was below 10 cm

Mt Washington was included in this portion of the study to analyze another mountain in the northeastern Appalachians. The meteorological classification results identified more winters as Maritime (4 out of 6 winters) than Continental (2 out of 6 winters) (Table 6). The decisive criteria for these classifications were total rainfall over 80 mm (Maritime) and average temperature below -7°C (Continental). Despite the prevalence of Maritime winters, the average temperature (<-7°C) and average December temperature gradient (>10°C/m) corresponded to the Continental climate (Table 6). According to the Wilcoxon-rank sum test result, air temperature, snow height and mean December temperature gradient were more similar to the Chic-Chocs than to the Gaspé North Coast, with around 300 mm SWE and 100 cm of snowpack (Table 6).

2.3.2 Grain type distribution

The Chic-Chocs range was dominated by faceted crystals and depth hoar (38.3%) (Figure 6). In opposition to faceted grains, rounded grains (9.5%) represented a low temperature gradient. Precipitation particles (including fragmented particles) and melt forms were the second most-present grain type both at 24.5% (Figure 6). For the Gaspé North Coast area, the most prevalent snow grain type was melt forms and ice formations at 32.8% (Figure 6). The second most prevalent snow grain type was precipitation particles (including fragmented particles) at 26.7%. Faceted crystals and depth hoar were the third most prevalent at 22.4%. Rounded grains (12.4%) were more prevalent than in the Chic-Chocs (Figure 6).

Faceted crystals and depth were more presented in the Chic-Chocs compare the Gaspé North Coast, and were also significantly different ($w=16$, $p\text{-value}<0.05$). Melt forms and ice formations were more present on the Gaspé North Coast but were not significantly different ($w=13$, $p\text{-value}>0.05$). Fragmented precipitation particles represented the second most prevalent snow grain type in both study areas, 24.5% to 26.7%. These results suggested three main snow grain types for the two study areas combined: Faceted crystals and depth hoar (30.4%), melt forms and ice formations (28.7%) and precipitation particles and fragmented particles (25.7%).

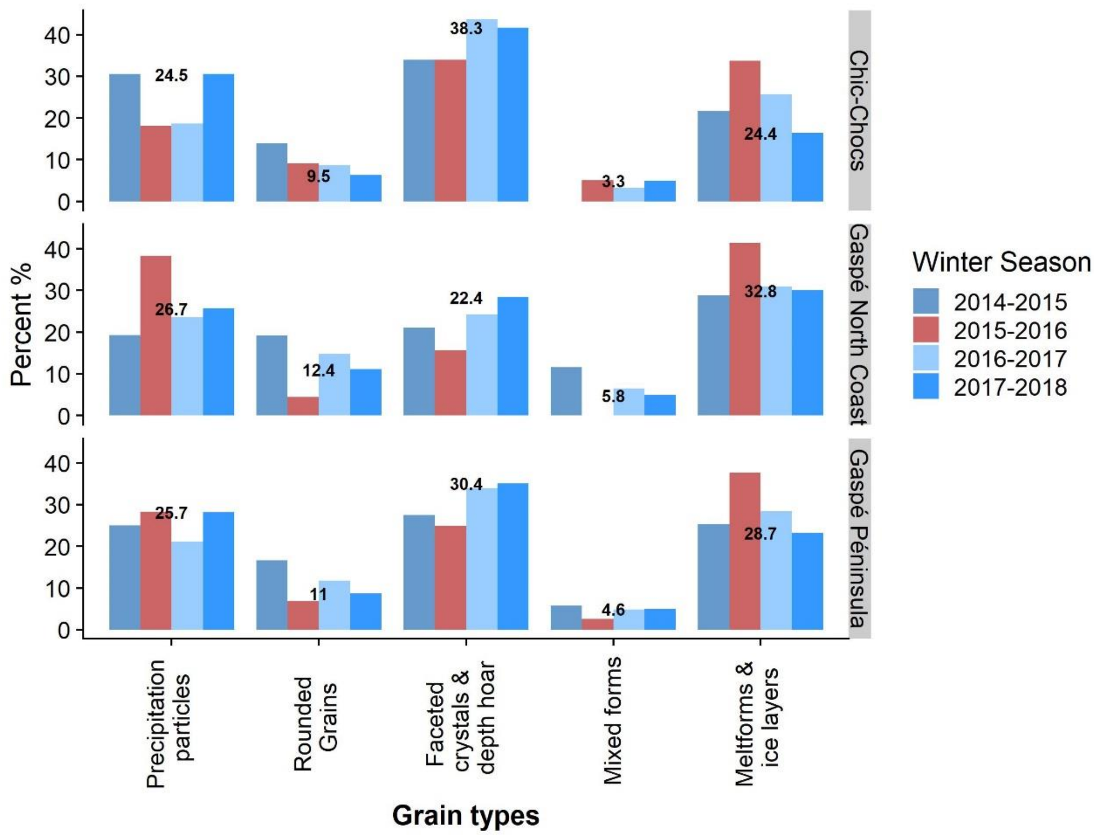


Figure 6. Graph of the presence of snow grains type for the winter seasons 2014-2015 to 2017-2018. The number is the average of all winter seasons. The colour of each year represents the snow-climate classification (Table 6): blue for Continental winters and red for Maritime winters.

2.3.3 Avalanche Problem type distribution

The analysis of past forecasting data revealed a dominant snow avalanche hazard (Shandro & Haegeli, 2018). In every winter, the region was characterized by the dominance of the wind slab avalanche problem type (58.5%). The prevalence this type of avalanche problem was relatively stable through several winters. However, winter 2013-2014 and 2015-2016 recorded significant anomalies in wind slab instability (-10.8 percentage points-p.p. and +9.2 p.p. respectively) (Figure 7-B). The storm slab and loose dry avalanche problem types were also relatively stable through several winters, with a prevalence of 7.8% and 4.6% each year respectively. Wet slab and loose wet avalanche problem types show negative anomalies with none of these types of instabilities for the season 2013-2014 and 2014-2015 (-2.0 p.p. and -3.5 p.p.). These seasons also had the most persistent slab instabilities with +8.8 p.p. and +14.6 p.p. (Figure 7-B). The persistent slab problem type has the most variable anomalies throughout all winter, with an average of 9.6% (Figure 7). The 2012-2013, 2015-2016 and 2016-2017 seasons had practically no persistent instabilities (-8 p.p., -9.6 p.p. and -8.8 p.p.). Cases in which no avalanche problem was published represent 14% for all winter (Figure 7-A).

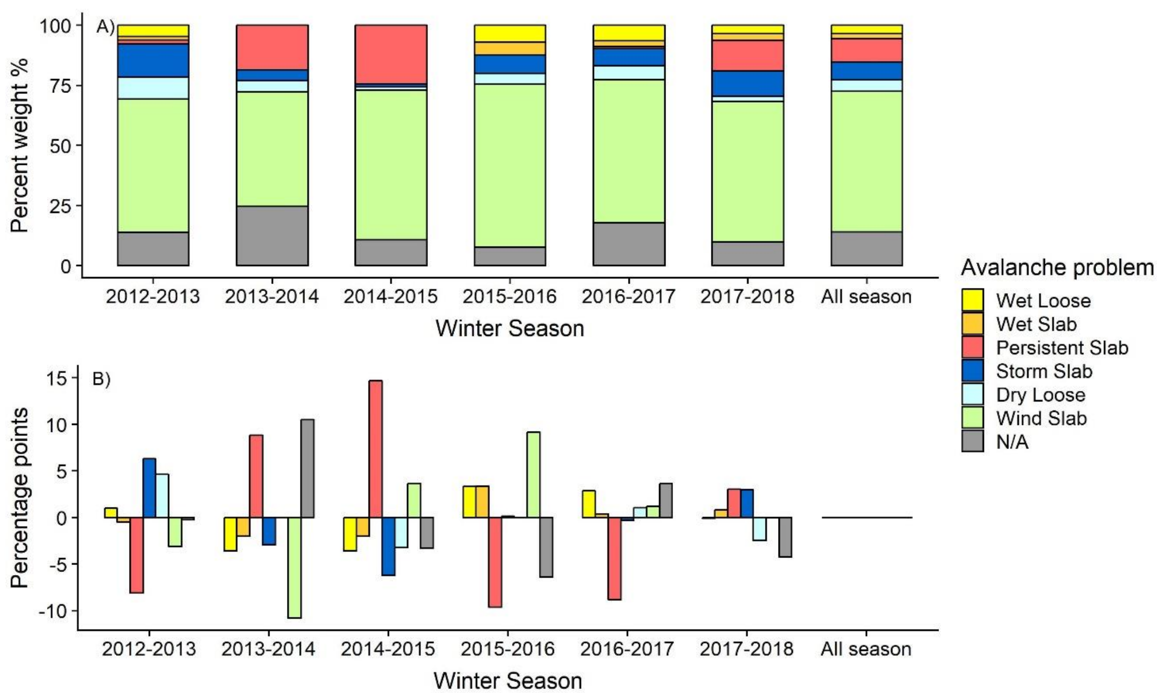


Figure 7. Avalanche problem types in the Chic-Chocs as reported by Avalanche Québec forecasting data for the winters 2012-2013 to 2017-2018, Chic-Chocs range data only. (A) Avalanche problems for each winter and the percentage of mean avalanche problems for all winter. (B) Anomalies in percentage points for each winter are represented by the difference from the means of all winter.

For the Gaspé North Coast and the Chic-Chocs, wind slab and non-avalanche problems were the most variable avalanche problem types (Figure 8). Wind slab instabilities were more present in the Chic-Chocs range by 26% and 37% for 2016-2017 and 2017-2018 respectively (Figure 8-B). Non-avalanche problems were more present along the Gaspé North Coast by 19 p.p. to 30 p.p. Persistent slabs were more present during winter 2016-2017 along the Gaspé

North Coast (5.6%); the opposite was true during 2017-2018 winter in the Chic-Chocs (11.7%) (Figure 8). Storm-related instabilities such as storm slab and dry loose avalanche problem types were similar in both areas.

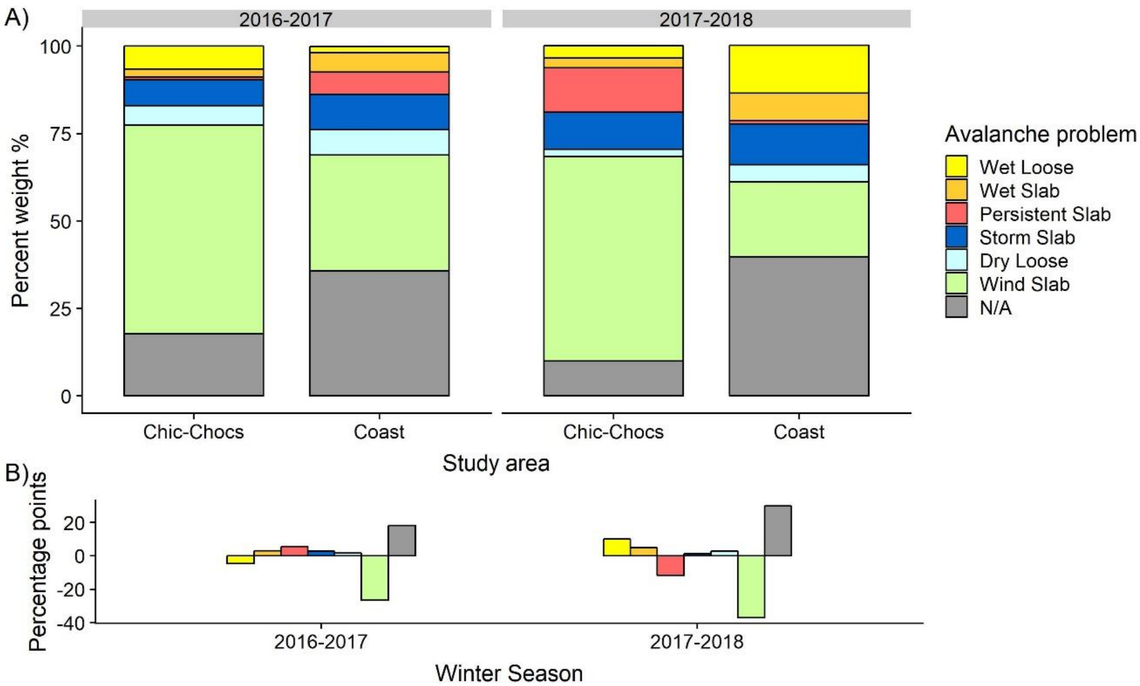


Figure 8. Comparison of avalanche problems in the Gaspé North Coastal area and the inland massif. (A) Avalanche problem by area, broken down by year. (B) Difference in percentage points between the two study areas for each avalanche problem type (positive/negative means more/less in the Gaspé North Coast).

2.4 DISCUSSION

2.4.1 Regional characteristics and variability

The meteorological classification results indicated a Continental winter with some Maritime winter. The meteorological variables between Maritime winters and Continental are similar except for the rainfall that exceeds 80 mm. The Maritime winter of 2015-2016 produced more melt-freeze crust and less faceted crystal compared to Continental winters, for the two study area (Figure 6). Maritime winters also experience negative anomalies for persistent slab problem type and positive anomalies for wet slab and loose avalanche problem type compared to Continental winters. However, the winter 2016-2017 has been classified Continental but the avalanche problem type distribution exhibit the same “maritime pattern” rather than continental (Figure 7). The Continental winters 2013-2014 and 2014-2015 experienced the coldest mean air temperature and the absence of significant thaw events to create wet slabs and loose wet avalanche problem types (Table 6 and Figure 7). Despite some Continental and Maritime winters, Wind slab avalanche problem type prevailed for the two study area, with storm slab avalanche problem type in second. The combination of the three methods helps to see different pattern in terms of snow grain type and avalanche problem type distribution for Maritime and Continental winters. However, more data are needed to clearly identify “typical Maritime and Continental seasonal pattern”.

The presence of rain-on-snow event on all winter (Continental and Maritime) can also generate major wet avalanche cycles or cause the refreeze of the saturated isothermal snow layer. The Gaspé Peninsula experienced several of these thaw events increase the ice layering in the snowpack, which is also experienced on other mountains in the northeastern Appalachians, such as Mt Washington (Joosen, 2008). Regional climatic conditions and snow grain type distribution suggested cold temperature favorable for facet metamorphism and thaw events creating subsequent ice layers. Together, these snow grain types produce the conditions for the development of a persistent weak layer (Jamieson, 2006). However, when saturated layers refreeze or strong winds produce extremely dense hard wind slab, they create a bridge in the upper snowpack and can prevent fractures in the lower weak faceting snowpack (Joosen, 2008). This process of “bridging” could explain why no persistent avalanche problem type are forecasted during the winter. Faceted crystals on melt-freezed crust could develop to become a persistent weak layer but strong layer above in snowpack are created to prevent fracture on this particular weak layer. This could be an explanation for the continental winter of 2016-2017, who look like maritime winter in terms of avalanche problem type distribution (negative persistent avalanche problem type anomaly). It could also explain low percentage of persistence slab problem for a Continental snow-climate in comparison with Continental areas in western Canada (Shandro & Haegeli, 2018). This process should be refined in future research for the Gaspé Péninsula.

Results of the meteorological classification showed no difference between the Chic-Chocs and the Gaspé North Coast with Continental and Maritime results. However, differences remained with warmer temperature and less precipitation along the Gaspé North Coast (Table 6). Snow precipitation related classification criteria indicated less accumulation along the Gaspé North Coast (Table 6). These results show an altitudinal gradient and a distance to the Gaspé North Coast gradient, also described by Gagnon (1970). Differences in the presence of faceted crystals (more in the Chic-Chocs) and melt-freeze crusts (more on the Gaspé North Coast) could indicate more maritime influence near the Gaspé North Coast. However, this is not in agreement with higher values of mean December temperature gradient observed in the Gaspé North Coast and showed that using the mean December temperature gradient where very thin snowpack might not be relevant or use with caution (discuss below in section *data quality and reliability)*. The avalanche problems type distribution between the Gaspé North Coast and the Chic-Chocs was variable. Constant strong wind causes snow erosion, stripping the snowpack down to ground level on the majority of avalanche-prone slopes in the Gaspé North Coast area (B Hétu & Bergeron, 2004; B. Hétu & Vandelac, 1989). This wind regime could explain the strong presence of non-avalanche problems along the Gaspé North Coast. Persistent slab problem type was also variable between the two study areas. During the winter season 2016-2017 and 2017-2018, the two study area were both classify as continental winter and look similar in terms of climatic conditions (Table 6) and snow grain type distribution (Figure 6). Persistent slab problem type was more present on the Gaspé North Coast than the Chic-Chocs during the winter 2016-2017 (Figure 8). This situation is the same for 2017 and 2018 except it is more present in the Chic-Chocs. The use of avalanche problem type data gives in insight on seasonal avalanche hazard situation that could not be outlined by the two other methods. However, our dataset and methods could not show when or why persistent problems are more present on the Gaspé North Coast or the Chic-Chocs during a particular season. Many factors could explain the difference between the avalanche regime of the Gaspé North Coast and the Chic-Chocs. Future studies should address the difference in altitude, the proximity of the St. Lawrence and the trajectory of low-pressure cells to possibly explain major differences in meteorological conditions, snowpack structure ("bridging" process) and ultimately avalanche hazards.

2.4.2 Global comparison

In order to compare our data with a potentially similar location around the globe, we adapted the boxplot figure from Mock & Birkeland (2000) with each decisive flowchart criterion to visually compare each region mentioned above. We also used data directly from the paper of Ikeda *et al.* (2009) for the Central Japanese Alps, who is also similar to the Gaspé Peninsula. The decisive criteria used by the flowchart were the December temperature gradient over 10°C/m (Continental) and total rainfall over 80 mm (Maritime) (Ikeda *et al.*, 2009). These decisive criteria were in similar ranges to those for the Gaspé Peninsula (Figure 9). The SWE, snowfall and December temperature gradient for Central Japan were more like the Chic-Chocs range rather than the Gaspé North Coast. However, the air temperature was similar to the Gaspé North Coast of the Gaspé Péninsula. The amount of rainfall was similar in all four areas (the Gaspé North Coast, Chic-Chocs, Central Japan and Mt Washington) (Figure 9). We also compared all four areas with the three classic snow-climates of the western United States (Mock & Birkeland, 2000). Snow-related parameters, such as the SWE, snow height and December temperature gradient were in the range for a Continental snow-climate (Figure 9). Air temperature was also in the range for a Continental climate, with the Chic-Chocs and Mt Washington at the lower end of the range (colder) and the Gaspé North Coast and Central Japan at the upper end of the range (warmer) for (Figure 9). Rainfall was the only decisive criterion in the Maritime snow-climate range for all the regions. Average rainfall across all regions ranges from around 49 mm (Gaspé North Coast) to 94 mm (Mt Washington) (Table 6). These results indicate that all the regions including Gaspé North Coast, Chic-Chocs, Mt Washington and Central Japan were similar to the Continental snow-climate except rainfall, in which they were similar to a Maritime snow-climate (Figure 9).

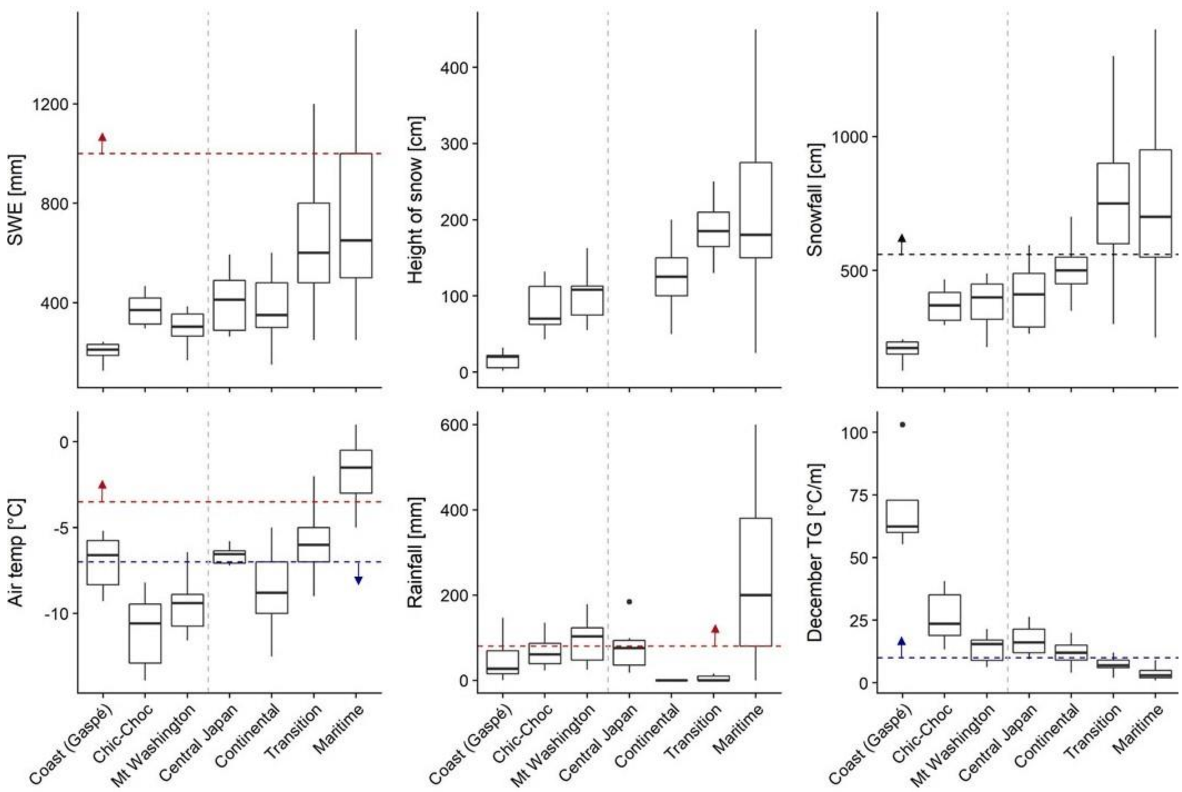


Figure 9. Box plot adapted from Mock & Birkeland (2000) with the results of all the decisive criteria from the flowchart. Horizontal dashed and the arrows represent the threshold for every decisive criterion (Table 5-B), blue are continental, black transitional and red maritime. Vertical dashed line separated our data from others: Data for Central Japan was taken from Ikeda *et al.* (2009) and for Continental/Transitional/Maritime snow-climates from Mock & Birkeland (2000). **© American Meteorological Society. Used with permission.**

If we compare these results from the snow-climate classification with data from western Canada (Shandro & Haegeli, 2018), Continental and Maritime winters are not common in the same area. Transitional area, the Columbia Mountains, has mostly Transitional winters and some Continental and Maritime winters. From the avalanche problem perspective, the Gaspé Péninsula has quite the same pattern as the Coastal mountains (Maritime snow-climate), Sea-to-Sky and South Coast Inland. Thus, the snow-climate of the study area does not fit into the three classic snow-climates developed in the western North-America. Our study area had similarities with Continental regions for all meteorological variables except rainfall (Figure 9). Other regions of the world such as Mt Washington and the Central Japanese Alps had the same pattern of small amounts of snow precipitation, cold air temperature and significant amount of rainfall during winter (Figure 9).

The snow grain type distribution and climatic conditions of the study area can be compared with those studied in Svalbard, Norway (Eckerstorfer & Christiansen, 2011). Both snowpacks have similarities: they are cold and thin with the dominance of facet metamorphism process. Both have basal instabilities and faceted crystals caused by cold winter temperatures. They are also affected by maritime depressions with warm air and rain causing ice layering in the snowpack. Similar to Svalbard, these results showed the specific context of the Gaspé Peninsula with snow grain type from a Continental climate (facet and depth hoar) and Maritime climate (ice layering). Snowpack and climatic data showed two major snow-climate components: a cold snowpack combined with maritime influence causing rain-on-snow events.

Ikeda *et al.* (2009) described two study areas in the Japanese Alps: the Japanese Coastal Mountains (northern Japanese Alps) and the Central Japanese Alps. This research showed similarities between the Central Japanese Alps and the Gaspé Peninsula. Both regions obtained the same snow-climate results with the Mock & Birkeland (2000) flowchart: Continental winters with Maritime winters (Ikeda *et al.*, 2009). The decisive criterion used for the classification are also similar, with a Continental winter mean December temperature gradient (DEC TG>10°C) and a Maritime winter rainfall (>80 mm) (Ikeda *et al.*, 2009). The climatic conditions were similar, including cold air temperature, small amounts of snow precipitation and significant rainfall (Figure 9).The snowpack structures were also comparable, with a strong prevalence of faceted crystals and melt forms (Ikeda *et al.*, 2009). The authors observed that the characteristics described above did not correspond to any of the three main snow-climate classifications. They proposed a new classification for the Central Japanese Alps, Rainy Continental snow-climate. This new classification is defined by the following specific characteristics (Ikeda *et al.*, 2009): “1) A relatively thin snowpack and cold air temperatures, which have the same range as Continental snow-climate regions. 2) Heavy rainfall with the same range or a greater range than Maritime snow-climate regions.

3) Persistent structural weaknesses caused by faceted crystals and depth hoar similar to Continental snow-climate regions. 4) The dominance of both faceted crystals and wet grains."

2.4.3 Snow and avalanche climatology

A new snow-climate classification is needed to fully describe the specific climatic context of these regions. In the past, the Gaspé Peninsula has been classified in the Maritime snow-climate according to the Sturm *et al.* (1995) global classification, solely based on climatic variables such as temperature and precipitation, and without any consideration of snowpack or avalanche regime (Sturm *et al.*, 1995). Other authors have used the term Cold Maritime to describe the region (Fortin *et al.*, 2011; Gauthier *et al.*, 2017). Joosen (2008) used that same nomenclature for similar coastal mountains areas in northeastern North America, such as Mt Washington in the eastern United States.

The Gaspé Peninsula has similarities with several regions of the world such as Mt Washington and the Central Japanese Alps. All of these regions are influenced by cold air masses from the continent but also by low-pressure cells from the ocean. These specific influences of both continental and maritime low-pressure cells have been previously observed for the northeastern coast of the United States (Karmosky, 2007; Perry *et al.*, 2010). This is in contrast with the coastal mountain ranges of the northwestern United States, which are influenced primarily by maritime low-pressure cells. The four characteristics mentioned above for the Rainy Continental classification of the Central Japanese Alps are identical on the Gaspé Peninsula. However, Rainy continental express continental and maritime influence like a Transitional snow-climate. Haegeli & McClung (2007) proposed the idea that other Transitional snow-climate region should be studied to highlight dominant process different from the Columbia Mountains. The Transitional snow-climate could be expanded to include multiple types of Transitional snow-climate where the mix of continental and maritime influence leads into certain types of dominant process for snowpack weakness, such as the prevalence of surface hoar layer in the Columbia Mountains (Haegeli & McClung, 2007).

We thus propose to expand the Transitional snow-climate type to include Rainy Continental snow-climate. This snow-climate is used for the Central Japanese Alps and with further analysis could also be used for Mt Washington and Svalbard. The term Rainy Continental expresses both the major Continental component and the Maritime influence. This term might be a better fit for insular/peninsular or northeastern coastal Continental snow-climates rather than any of the three main snow-climates developed in the much bigger mountain ranges of the western United States. The term Rainy Continental, as a part of the Transitional snow-climate type, has specific characteristics mentioned by (Ikeda *et al.*, 2009). Our data indicate the same specific characteristics describing snow-climate. These characteristics can be used to classify new regions in the Rainy Continental snow-climate type.

Avalanche forecasting programs in the study area has adapted to these following characteristics. Avalanche forecast programs in Rainy Continental areas could focus mainly on weather observations (non-automated and automated weather stations). The presence of persistent slab is low (around 10%) (Figure 7), but is likely to cause more accidents due the difficulties associated with assessing and recognizing signs of instability in avalanche terrain (Haegeli *et al.*, 2010). These forecast program could or are also adapted to particular persistent weak layer, mainly faceted crystals on melt-freeze crust. This type of persistent weak layer has a specific spatial distribution, instability and require a procedure to manage this instability that is different, for example, from surface hoar layer in the Columbia Mountains (Haegeli & McClung, 2007). Thermodynamic snowpack modelling with meteorological data has been used in Switzerland to assess snowpack characteristics for avalanche forecast program (Lehning *et al.*, 1999). Implementation of snowpack models into the avalanche forecast program will optimize snowpack assessment while reducing effort in the field. A good weather station network could be used to assess different areas where snow profiles are carried out. If weak layers are simulated by the model, forecasting teams could concentrate their efforts by testing these weak layers in the field for further validation. Snowpack models should not be seen as a replacement for avalanche technician field teams but more as a tool to concentrate efforts for efficient field assessments. Snowpack models could be a good implementation for this type of Rainy Continental snow-climate when snow profiles are not always required. This implementation could optimize avalanche forecasting efficiency in Rainy Continental snow-climate areas.

2.4.4 Methodology review and limitations

Each of our type of data and method suggests a component of the three main snow-climate type. The outcome of the meteorological classification of Mock & Birkeland (2000) directly lead to a snow-climate type compared to two other methods who need more interpretation. For each winter of our dataset, we observed two distinct scenarios when looking at the outcomes of the three different methods: (1) suggest the same snow-climate type and (2) when the outcomes were different. The first scenario is a start to characterise typical continental winter and maritime winter with three complementary perspectives: meteorological conditions, snow grain distribution and avalanche problem type distribution. However, more data are needed to identity typical pattern of Continental and Maritime winter in a Rainy Continental snow-climate type.

The second scenario highlights the limitations of one of the methods for a particular situation. For example, the Gaspé North Coast has high values of mean December temperature gradient compared to the Chic-Chocs. However, this result is not in agreement with more presence of faceted crystals in the Chic-Chocs compared to the Gaspé North Coast. The mean December temperature gradient on the Gaspé North Coast could be an issue. For some days in December, the snowpack is thin or non-existent, resulting in high temperature gradient values (Table 6). Furthermore, assuming zero degree Celsius at the base of the snowpack could also cause high temperature gradient values, especially for a snowpack that is too thin to isolate the ground from air temperature. The discrepancies between the methods also help to highlight “exception or unusual winter” like the 2016-2017 winter. This winter was classified as Continental but show a maritime pattern in the avalanche problem type distribution. The use of only one method, such as the meteorological classification, could not have shown this “unusual winter.” These two examples show the limitations of the meteorological classification who only highlight general weather conditions. The forecast data also had certain limitations. Variability between winters can be attributed to changes in forecasting guidelines each winter (Shandro & Haegeli, 2018). The methodology chosen for the distribution of the avalanche problem type simply present the proportion of which type of concern the forecasters are dealing with during the winter. It doesn't account for typical situation when two or more avalanche problem types are issued the same day, for example persistent slab avalanche problem and wind slab avalanche problem. Shandro & Haegeli (2018) propose a much more complex and detailed methodology to characterise the nature of avalanche hazard in western Canada. However, for the purpose of snow-climate classification, we choose a simplified approach to simplify the outcome and the comparison with the other types of data and methods.

The use of different types of data and especially forecasting data is only suitable for existing forecasting programs who have several seasons of data to build a dataset and not very interesting for mountainous regions with no forecast program. It also represents a challenge to establish a complete dataset for several seasons. Our dataset expresses this challenge with only six winters of meteorological data, four winters of snow profile and six winters of forecasting data for the Chic-Chocs (only two winters for the new forecasting program of the Gaspé North Coast). This represents the main limitations of our study when climatic studies have longer datasets, usually over a decade or more. Even if the results observed in this paper represent a small period of time and further data are needed, the characteristics observed on snow-climate with an avalanche perspective, are still a valuable addition to the present knowledge on climate for the study area.

2.5 CONCLUSION

In this study, we presented a snow-climate classification specific to the Gaspé Peninsula. This classification can be applied to northeastern Gaspé North Coastal climates characterized by Rainy Continental climate. We used several proven methodologies to fully characterize the snow-climate of the study area. This methodology demonstrated the benefit of using multiple types of data and should be considered for future snow and avalanche climate studies. Mock & Birkeland (2000) flowchart results revealed two major components of the snow-climate: Continental and Maritime. Snow profile data showed the same two components: a cold snowpack with a dominance of facets and ice layering mostly caused by rain-on-snow events. This combination of two major grain types produce the appropriate conditions for the development of a persistent weak layer such as a facet/crust interface. Avalanche problem data confirmed the presence of persistence instabilities in both study areas. It also revealed seasonal variability for every avalanche problem type, which could be related to climatic conditions. The climatic and snowpack characteristics of the study area were similar to the Central Japanese Alps (Ikeda *et al.*, 2009) and Mt Washington, U.S.A. The term Rainy Continental proposed by Ikeda *et al.* (2009) is defined by a snow-climate with a major Continental component and a Maritime influence. We therefore propose adopting the term Rainy Continental for the Gaspé Peninsula, as a part of the Transitional snow-climate type.

2.6 ACKNOWLEDGEMENT

We will like to thank Avalanche Québec and Mt Washington Avalanche centre for their data. This research was funded by MITACS, Ministère des Transports du Québec and Natural Sciences and Engineering Research Council of Canada (NSERC).

CHAPITRE 3
VARIABILITÉ SPATIALE DES PROPRIÉTÉS DU MANTEAU NEIGEUX : UNE COMPARAISON ENTRE UN VERSANT ENNEIGÉ CÔTIER ET EN VALLÉE, GASPÉSIE, CANADA

3.1 RÉSUMÉ EN FRANÇAIS DU DEUXIÈME ARTICLE

La variabilité spatiale des propriétés du manteau neigeux est la principale incertitude en prévision des avalanches. Cette variabilité spatiale détermine l'occurrence spatiale et la taille probable d'une avalanche. À l'échelle régionale, cette variation est expliquée par les facteurs topographiques (angle de pente, orientation et altitude). À l'échelle d'une pente, la variabilité spatiale pourrait être expliquée par l'interaction complexe des processus météorologiques et le terrain. Les routes provinciales 132 et 198 situées au nord de la péninsule gaspésienne sont menacées par des avalanches de neiges sur de petites pentes côtières et en vallée de basse altitude. Ces pentes ont un régime spécifique d'avalanches, qui diffère du régime des Chic-Chocs, situé en arrière-pays. Des analyses de séries temporelles ont souligné la variabilité de deux régimes de vent (vitesse et direction) et du bilan radiatif de surface, entre les deux sites d'étude (côte/vallée). À l'échelle de la pente, des analyses géostatistiques ont démontré l'influence de la végétation sur deux différents patrons d'accumulation et d'ablation de neige par le vent. Ces connaissances sur la variabilité spatiale du manteau neigeux et plus spécifiquement sur l'accumulation et l'ablation de la neige devraient améliorer la prévision et le programme futur de mitigation des avalanches de neige.

Ce deuxième article, intitulé « *Spatial variability of snowpack properties: comparison between coastal and valley avalanche-prone slopes in northern Gaspésie, Canada*» fut rédigé par moi-même en tant que premier auteur. Le professeur Francis Gauthier, le professeur Alexandre Langlois m’ont accompagné dans le processus intellectuel et dans la révision de l’écriture de cet article. Cet article devrait être soumis dans la revue *Physical Geography* au printemps 2019.

Spatial variability of snowpack properties: comparison between coastal and valley avalanche-prone slopes in northern Gaspésie, Canada.

3.2 INTRODUCTION

The spatial variability of snowpack properties is the main uncertainty in avalanche forecasting (Schweizer *et al.*, 2008) while determining the spatial occurrence and potential size of snow avalanches (Kronholm & Schweizer, 2003). Snow and avalanche research focused on the spatial variability of snowpack properties can be grouped into two spatial scales: 1) regional/mountain range and 2) slope scale (Schweizer *et al.*, 2008). It has been shown that spatial variability at the regional scale is mainly driven by terrain characteristics (Birkeland, 2001; Feick *et al.*, 2007; Grunewald *et al.*, 2013; Jamieson, 2006; Reuter, van Herwijnen, *et al.*, 2015; Schweizer & Kronholm, 2007). Weak layer spatial distribution follows a "process-based terrain correlation" (Hägeli & McClung, 2003), reflecting variation of meteorological processes over terrain such as specific local wind regime (Feick *et al.*, 2007), valley clouds (Colbeck & Jamieson, 2006) and freezing level during storms (Jamieson, 2006). At the slope scale, although topographic parameters (slope angle, aspect and altitude) are relatively constant, the spatial variability of snowpack properties remains significant. On uniform glacier terrain, Sturm & Benson (2004) measure several snowpack properties and suggest that the cause of this variation could be linked to variations in external (meteorological) or internal (metamorphism) processes. Most studies on spatial variability of snowpack properties focused on persistent instabilities, mainly surface hoar crystals (e.g. Feick *et al.*, 2007; Kronholm & Schweizer, 2003; Lutz & Birkeland, 2011; Schweizer & Kronholm, 2007). This type of crystal has a specific spatial pattern mainly attributed to valley cloud (regional scale) and wind erosion (slope scale) (Feick *et al.*, 2007). Non-persistent crystals are also responsible for avalanche formation but the studies that integrate non-persistent grain type are limited (Kronholm & Schweizer, 2003; Landry *et al.*, 2004).

Several studies discuss the complex interaction between meteorological process and microtopography (Campbell & Jamieson, 2007; Guy & Birkeland, 2013; Kronholm & Schweizer, 2003; Lutz *et al.*, 2007; Reuter *et al.*, 2016). The studies above were mostly in alpine and subalpine areas and on uniform slopes (e.g. Campbell & Jamieson, 2007; Feick *et al.*, 2007; Kronholm *et al.*, 2004; Landry *et al.*, 2004; Lutz & Birkeland, 2011; Reuter *et al.*, 2016). Eckerstorfer *et al.* (2014) studied wind-affected coastal and valley slopes in Longyearbyen, Svalbard and showed that the interaction of terrain roughness with wind activity is responsible for slab thickness variations and therefore snowpack stability. They looked at three slopes in different valleys and at varying distances to the sea. However, they primarily attributed stability variations between the study sites to their different terrain roughness, rather than to their geographical positions or to the influence of meteorological processes (e.g. coastal or valley wind) (Eckerstorfer *et al.*, 2014).

Wind redistribution after snow precipitation events is mostly responsible for the spatial distribution of snow depth in mountain environments (e.g. Winstral *et al.*, 2002). This wind-driven snow depth spatial distribution depends mainly on terrain parameters (slope angle, altitude and aspect) and surface roughness (vegetation) (e.g. Deems *et al.*, 2006; Elder *et al.*, 1991; Erickson *et al.*, 2005; Mott *et al.*, 2010; Trujillo *et al.*, 2007, 2009). Trujillo *et al.* (2009) compare two adjacent areas (subalpine forest and alpine tundra) and demonstrate their different scaling properties and spatial snow depth distributions. Their findings suggest that snow depth varies on a smaller scale in the forested area, where it is determined by the spatial distribution of trees without a significant influence from wind redistribution, in contrast to the tundra area, where it is mostly driven by wind redistribution over ridges and depressions against the dominant wind direction (Trujillo *et al.*, 2009). These studies, mainly in alpine and subalpine water catchments, show the importance of vegetation distribution and characteristics to spatially predict snow depth. However, other environments in different snow climates need to be studied, such as small coastal and valley slopes with sparse vegetation distribution. Although the meteorological processes specific to coastal (e.g. Rotunno *et al.*, 1992) and valley environments (e.g. Barry, 2008) are well known and documented, the influence of meteorological processes on snowpack properties on small coastal and valley slopes, such as those found in Iceland, Norway and eastern Canada, has yet to be studied .

The north shore of the Gaspé Peninsula is threatened by snow avalanches. In 2016, Avalanche Québec started issuing daily avalanche hazard assessments for Québec's Ministry of Transport for avalanche-prone slopes adjacent to provincial roads 132 and 198. However in contrast to the alpine and subalpine slopes in mountainous regions such as Europe and Western America, the snowpack properties of these avalanche-prone coastal and valley slopes and their relationship to avalanche formation (e.g. Kronholm *et al.*, 2004) have not yet been studied. These slopes are highly affected by wind due to their direct exposure to the Gulf of St. Lawrence. This wind regime combines with topographic features specific to the study area (scree slopes with sparse vegetation) to create a snow accumulation pattern prone to avalanche formation (Germain *et al.*, 2010). This wind regime could be influenced differently by the surrounding terrain between provincial roads 132 (coast) and 198 (valley) (Figure 10). Most snow instabilities are caused by snow accumulation during snow storms (Fortin *et al.*, 2011; Gauthier *et al.*, 2017; Germain *et al.*, 2009; B Hétu, 2007). Gauthier *et al.* (2017) use logistic regression models to predict snow avalanches on these avalanche prone-slopes along these provincial roads. These models use meteorological variables to predict snow avalanche on the slopes next to provincial roads 132 (coastal) and 198 (valley). The models developed for the coastal avalanche slopes (provincial road 132) predict snow avalanches with snow accumulation over two days, rain of the current day and wind speed. However, the models for the valley slope (provincial road 198) predict avalanche with longer snow accumulation (three days), rain on two days and the temperature variation during the current day. These results indicate a variability of meteorological processes on snowpack properties and ultimately on snow avalanches between the coastal slopes and the valley slopes. Thus, better knowledge of the interactions between meteorological processes and the surrounding terrain, snow accumulation and snowpack properties of coastal and valley slopes is required in order to improve avalanche forecasting. The spatial distribution of vegetation cover on each slope also influences the spatial variability of snowpack properties. An improved understanding of this relationship could also improve avalanche forecasting and hazard management for these slopes. This study will mainly focus on snowpack properties, specifically the formation of dry slab avalanches caused by snow storms, as opposed to wet slab avalanches. Using two distinct spatial scales, it will look at inter- and intra-slope variability for the coastal and valley slopes, with three objectives:

1) Quantify and compare meteorological parameter variability between avalanche-prone coastal and valley slopes and its influence on snowpack properties.

2) Characterise spatial variability of snow depth and slab properties within each study site, with specific attention to vegetation distribution patterns.

3.1 STUDY AREA

3.1.1 Physical context

The study area is located on the north shore of the Gaspé Peninsula (Figure 10-A). The north shore of the peninsula is characterized by u-shaped valleys that run from the inland massif to the Gulf of Saint Lawrence (north-south). The erosion of the Gaspesian plateau (400-500 m elevation) has cut steep slopes (>30 °) into those north-south valleys and along the east-west shoreline of the Gulf of Saint Lawrence. Provincial road 132 squeezes between the Gulf of Saint Lawrence and a small coastal avalanche slope (50-80m long). Provincial road 198 is located in the valley of L'Anse Pleureuse, between a lake and a small valley avalanche slope (100-150m long) (Figure 10-a). The first study site is a Manche d'Épée (MAE), a coastal slope along provincial road 132 (Figure 10-c). The second is L'Anse Pleureuse (ANP), located in the valley of L'Anse Pleureuse (Figure 10-b). Both study sites have relatively uniform slopes with sparse vegetation distribution composed of bushes and trees. The MAE study site has a northern aspect facing the Gulf of Saint Lawrence, with a 38 ° slope, 100 m vertical drop and a rock wall at the top of the slope (Figure 10-c). The slope is around 50 m wide and is bounded by areas of dense vegetation (bushes and trees) that run from the bottom to the top of the slope (Figure 10-c). The ANP site has a southwest aspect, with a 35 ° slope, 150 m vertical drop and a rock wall at the top. It is two kilometers inland in the valley of L'Anse Pleureuse, which runs north-west/southeast (Figure 10). Vegetation zones are sparsely distributed in the middle of the slope, with several islands of vegetation and two open areas (10-20 m wide) along either side of the slope (Figure 10-b).

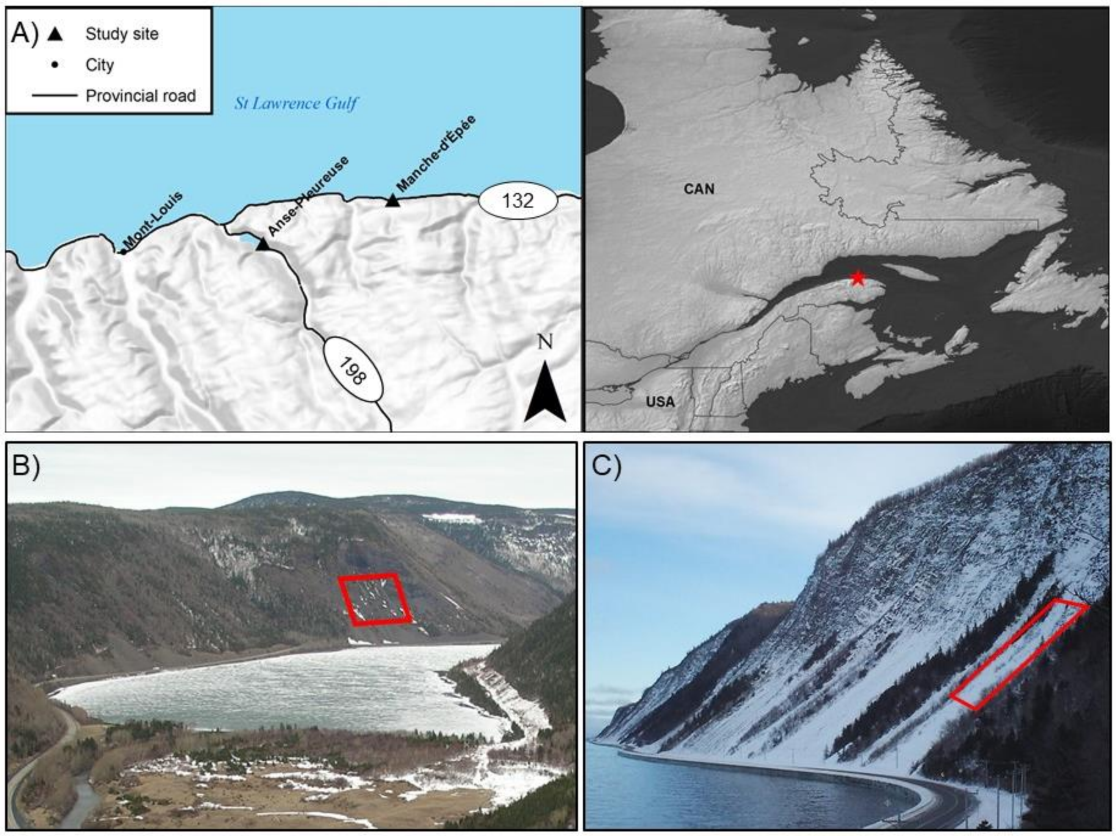


Figure 10. A) Study area with the two study sites located in northern Gaspésie. B) ANP valley study site (alt: 55 m a.s.l.). C) MAE coastal study site (alt: 46 m a.s.l.).

3.1.2 Climate

The study area is located on the north shore of the Gaspé Peninsula. The region receives 800 mm annually (Fortin *et al.*, 2011; Gagnon, 1970; Germain *et al.*, 2010). Snow falls typically from December to April, along with about 60 mm of winter rainfall (Fortin *et al.*, 2011). Mean annual temperature is 3 °C (Gagnon, 1970), while the mean winter month (December to March) temperature is around -8.4 °C (Fortin *et al.*, 2011). The regional climate is humid continental (Köppen classification Dfb) and characterized by contrasting air masses: 1) cold Arctic air masses that usually bring northwesterly winds (dominant wind direction) and temperatures down to -20 °C; and 2) continental low pressure systems with typically easterly winds at the beginning of the storm, temperatures near the freezing point and precipitation (Fortin *et al.*, 2011; Gauthier *et al.*, 2017). The region is affected by storms of various trajectories and origins (Alberta clippers, Colorado lows and Hatteras lows) (Fortin & Hétu, 2013). Snow storms are responsible for 90 % of avalanches on provincial roads 132 and 198 (Fortin *et al.*, 2011; Gauthier *et al.*, 2017; B Hétu, 2007).

3.2 METHODS

This study focuses on two distinct spatiotemporal scales. At the largest scale, the spatiotemporal variability of meteorological parameters and snowpack properties is analysed for two contrasted slopes, between a coastal and a valley slope, and for two winter months (February and March). An overview of the meteorological conditions during these two months is first provided. Then, the spatiotemporal variability of meteorological parameters for the coastal and valley slopes is determined using a detrend-cross-correlation analysis. We compare this spatiotemporal variability (detrend cross-correlation results) with several snowpack properties at the two study sites. At the smallest scale, spatiotemporal variability within each study site is investigated after two significant mid-March snow storms. This research focuses on snowstorm instabilities, which are mainly caused by the rapid accumulation of low-density snow during and after snowstorms (wind redistribution) on an older snowpack. Snow instability is related to three snowpack properties: snow height, slab thickness and slab mean resistance to penetration (Reuter, Schweizer, *et al.*, 2015). The spatial variability of these snowpack properties will be assessed in regard to snow instability. Using geostatistical analysis, we will estimate the spatial patterns of snow height and slab properties derived from punctual snow resistance measurements in each study area.

3.2.1 Weather data

Each study site is equiped with a weather station operated by the Laboratoire de Géomorphologie et de Gestion des Risques en Montagnes (LGGRM). These stations are installed directly on the slopes to monitor the effects of the surrounding terrain on meteorological processes. The stations (CR10x-Campbell Sci.) are equipped with instruments to record air temperature and relative humidity (HMP45C-L Campbell Sci.), wind speed and direction (R.M. Young 05103-10), incoming and reflected shortwave (Apogee SP-110), incoming longwave (Apogee SP-510), snow height (Campbell Sci. SR-50) and snow/soil temperature every 5 cm over 150 cm (custom-made) (Figure 11). The custom snow/soil temperature probe mounts thermistors (RoHS 100K6A1i-A ± 0.1 °C) every 5 cm along on a 2 cm x 5 cm x 150 cm PTFE bar (Polytetrafluoroethylene). The thermistor tips are flush with the surface of the PTFE bar, floating in a highly conductive epoxy (MG Chemicals-832TC). The first thermistor was placed at 5 cm into the soil and the second thermistor was placed at the snow/soil interface. The snow/soil temperature probe was placed facing north and painted white to reduced direct solar radiation exposure on the thermistor tip. Wind direction data were transformed into easting and northing components according to a method used for topographic aspects (e.g. Guy & Birkeland, 2013; Reuter *et al.*, 2016). Energy balance at the snow surface was computed with the following equation (e.g. Oke, 2002):

$$Q* = (K\uparrow - K\downarrow) + (L\downarrow - L\uparrow)$$

where Q* is the radiation budget at the surface, K↓ is shortwave incoming radiation, K↑ is the shortwave reflected radiation, L↓ is the longwave incoming radiation and L↑ is the longwave outgoing radiation. We assumed that the emitted longwave radiation by the snow surface was equal to the air temperature converted in W/m^2 with this following equation:

$$L\uparrow = \varepsilon\,\sigma\,T^4$$

where L↑ is the longwave outgoing radiation, ε is the surface emissivity assumed to be one, σ is the Stefan-Boltzmann constant, and *T* is the surface temperature in Kelvin assumed to be the same as the air temperature. We fixed the surface temperature at 273.15 K when air temperature was above 0 °C.

Consistent and comparable meteorological variables at each site were only recorded from February 1 to March 18 (15 minutes), 2018 due to a power supply issue on ANP site.

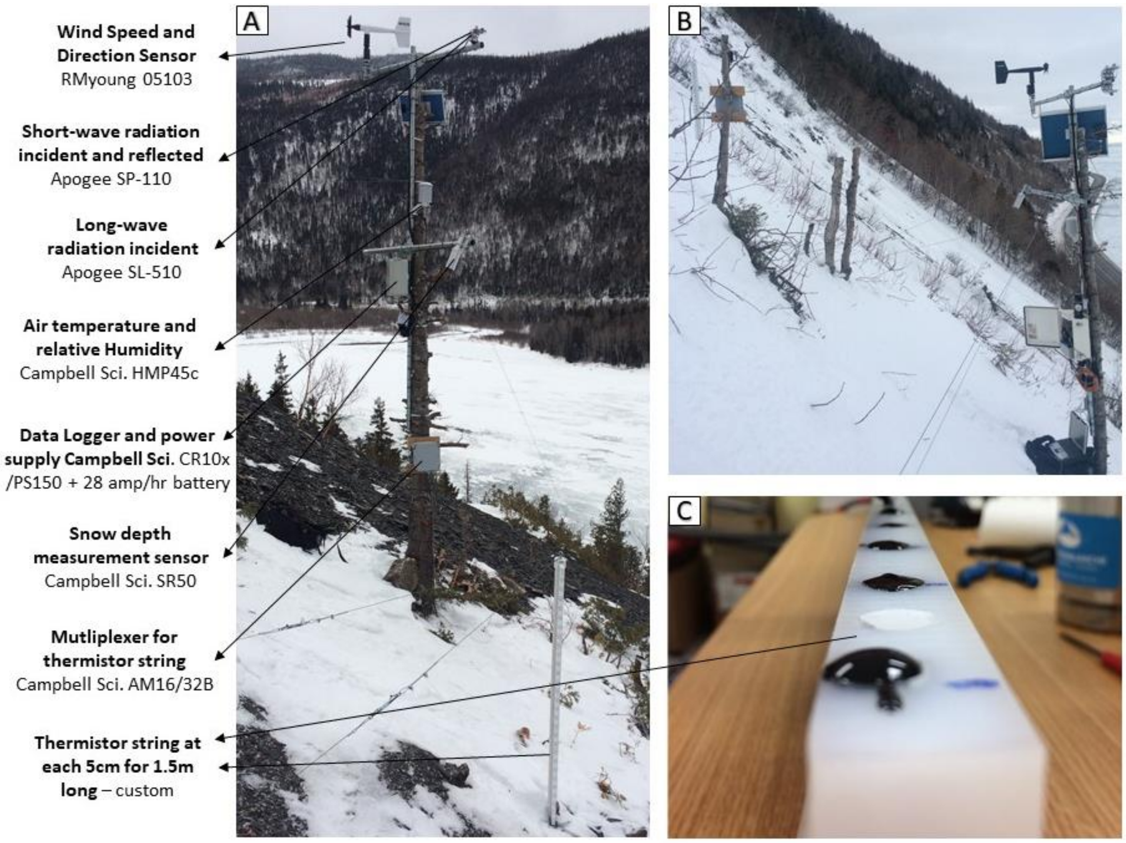


Figure 11. Weather stations installed directly on the slope: A) ANP weather station with a description of weather instruments. B) MAE weather station. C) Tip of thermistor mounted in a PTFE bar with high thermal conductivity epoxy. Thermistor tips were painted white after the epoxy hardened.

3.2.2 Snowpack data

Snow profile

Snowpack data were collected during a survey on March 18 and 19, 2018. No significant change in weather conditions was observed between March 18 and 19. We choose those specific dates to assess our study site after two consecutive snow storms on March 10 and March 14. With the Avalanche Québec forecasting team, we decided for safety to wait several days after the storms for the snowpack to stabilize. Snow profiles were dug to characterize the overall snowpack properties of the study site using the Canadian Avalanche Association methodologies in *Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanche* (CAA, 2014) including: snow height (cm), snow layer thickness (cm), snow layer hardness, snow grain type by layer, snow grain size (mm), density profile (Kg/m^3), snow temperature profile (°C), vertical resistance profile with the Avatech smartprobe 2 (KPa) and two compression test.

Penetrometer data and treatment

To assess snowpack properties (snow depth, slab thickness and slab mean resistance) across the slope, we used an Avatech (now MountainHub) smartprobe 2 (SP2). The SP2 is a penetrometer that measures the vertical resistance profile of snow using a 60 ° measurement cone tip (Avatech, 2016). Hagenmuller *et al.* (2018) evaluated the SP2 and showed its potential to track snow stratigraphy over space. However, they also demonstrated considerable measurement error for depth estimation and therefore the vertical position of layers. The measurement error was more significant in the upper snowpack and for soft layers (Hagenmuller *et al.*, 2018). Given this, we made three measurements at each location and used the Hagenmuller & Pilloix (2016) algorithm to merge the three profiles into one median profile (Figure 12). The matching procedure minimized the variability between the profiles without setting one as the reference. The following parameters were used: depth grid resolution 0.1 cm, layer transform resolution 4 cm, stretching factor bound 60 %, overall stretching factor bound 10 % (Hagenmuller & Pilloix, 2016). The matching algorithm was critical to reducing error in the vertical positioning of layers to precisely derive the slab thickness and slab mean resistance (Figure 12). SP2 measurement was impossible at some locations along the transect when snow depth was less than 30 cm or in the presence of bushes.

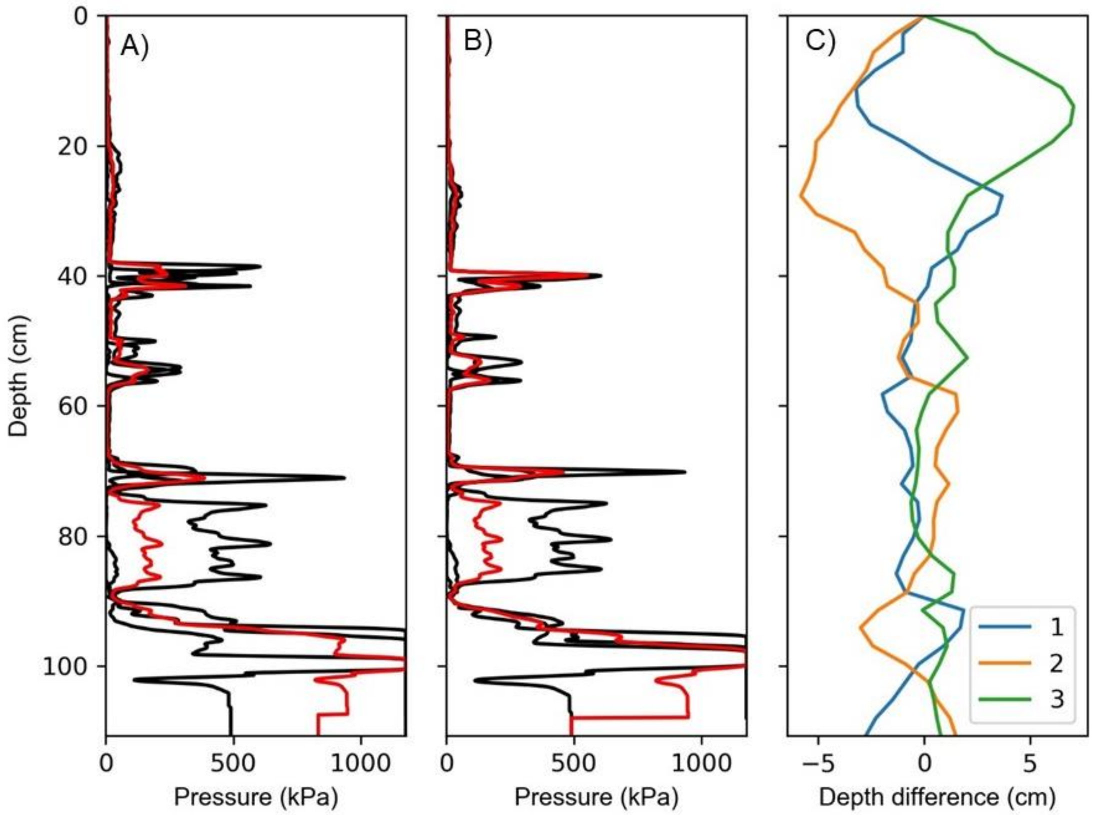


Figure 12. Example of the matching algorithm (Hagenmuller & Pilloix, 2016) with three SP2 profiles produced for one location along the transect. A) The three profiles before transformation. B) The three profiles after transformation with median profile in red. C) Transformation for each profile depending on the depth.

In order to determine slab thickness and slab mean resistance for every profile, we set an arbitrary threshold of 150 kPa (melt-freeze crust) and identified the depth at which the threshold was reached. The depth was used to derive the slab thickness and the corresponding slab mean resistance in kPa. The combination of soft snow overlying a melt freeze crust is a major feature in the resistance profile and could easily be tracked through multiple profiles (Figure 12). Snow height was manually validated with the SP2 snow probe. Snow height will characterize the overall seasonal snowpack and the slab parameters will characterize the accumulation of the last two snow storms.

Snow surveys were performed with the SP2 using site-specific spatial sampling grids (Figure 13). At first, our hypothesis on the snow accumulation pattern was that the slope was mostly cross-loaded because of the rock wall blocking any snow transport from the top. This hypothesis guided our snow sampling choice to assess horizontal variability along the slope instead of vertical variability. We choose to make three horizontal transects, each 10 m from one other to assess the slope (Figure 13). Using multiple transects instead of a more complex sampling grid improves snow sampling efficiency, thereby minimizing time of exposure on an avalanche slope. The minimum spacing between measurements on the transects was 2 m for the 46 m long MAE transect and 3m for the 60 m long ANP transect (Figure 13).

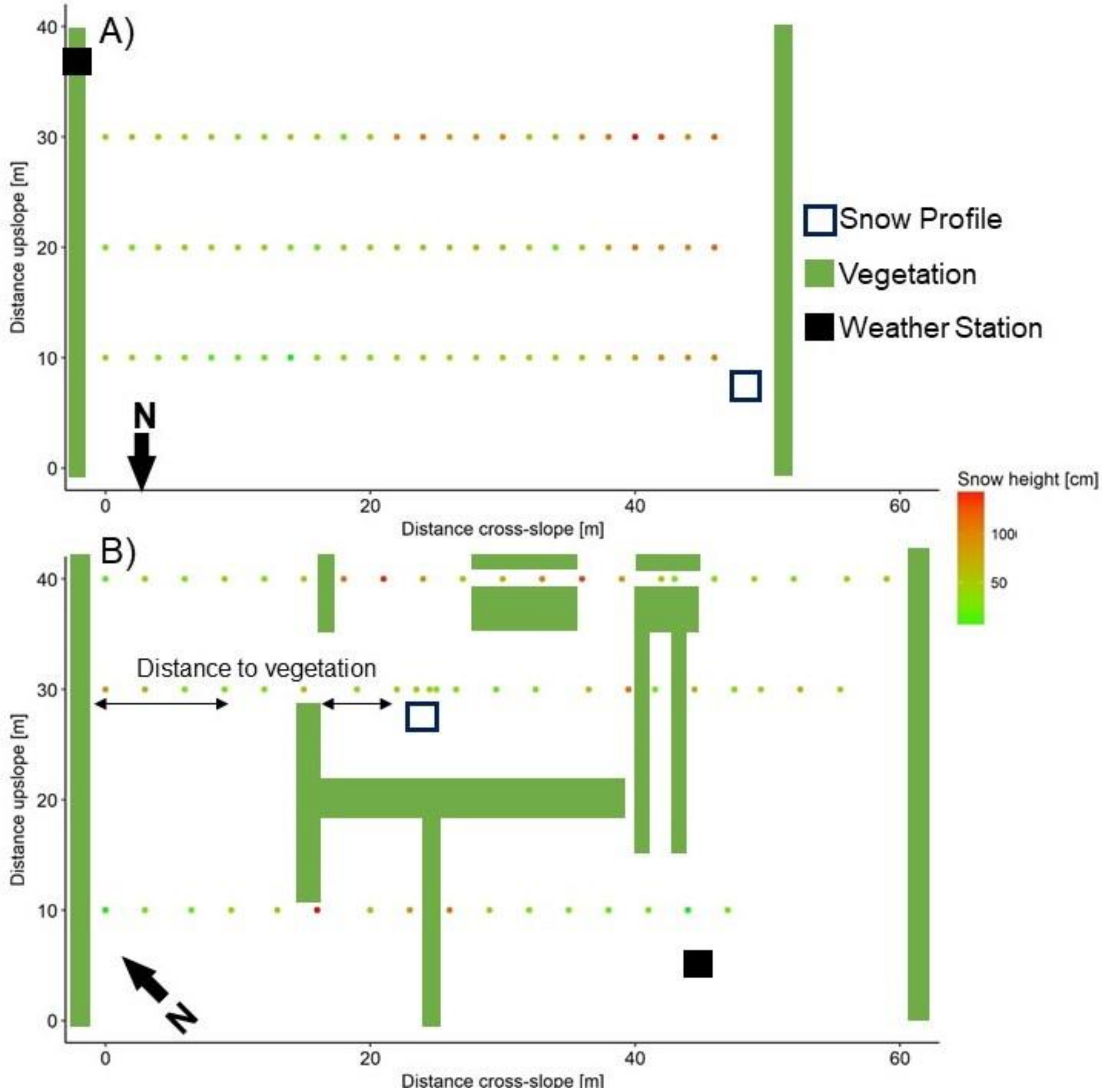


Figure 13. Site-specific snow sampling grids. A) MAE sampling grid from March 18. B) ANP sampling grid from March 19. Distance to vegetation is an example of the covariate explained below for the geostatistical analysis.

3.2.3 Statistical analysis

Time series analysis

In order to compare the influence of weather processes on snowpack properties at each site, we used the cross-correlation function to determine the correlation between two time series (same meteorological variable for the two study site), but required second-order stationarity (Chatfield, 2004). Each meteorological variables is represented in a time series that can be decomposed into three components: a trend component, a seasonal/cyclic component and an irregular component. Stationarity is achieved when mean and variance is stable over time and any significant trend and/or seasonal component make stationarity impossible (e.g. Goela *et al.*, 2016; Vantrepotte & Mélin, 2010). Trend and seasonal component removal is required to perform a cross-correlation analysis. Stationarity was assessed using the auto-correlation function and a transformation was applied (detrend and/or seasonality) depending the interpretation of the auto-correlation function (Chatfield, 2004). We assessed the trend and seasonal components within different sized moving windows to test different temporal scales (12 h, 24 h, two days, one week) and then removed them from the time series. Residual trend could overestimate the cross-correlation coefficient. The result showed a measure of similarity for meteorological processes between the study sites. The cross-correlation function can also determine the time shift according to the highest cross-correlation coefficient. All cross-correlations were with ANP over MAE. Thus, a negative time shift indicates the process occurred first at ANP and a positive time shift indicates it occurred first at for MAE. The *stats* package (version 3.3.1) in R studio (RStudio, 2016) was used for auto-correlation, decomposition, transformation and cross-correlation.

Geostatistical analysis

In order to estimate spatial variability within each study site, we performed geostatistical analysis on the three main snowpack properties derived from the vertical resistance profile (SP2): snow height, slab thickness and slab mean resistance. This strategy was used by Reuter *et al.* (2016) to show spatial patterns of snow instability with a spatial model using a background field (linear model) and residual autocorrelation (variogram). The background field is a linear model that uses the position of each observation and some covariate to spatially explain the response variable. The linear model was built using stepwise multiple linear regression with spatial variable such as(e.g. Reuter *et al.*, 2016) the coordinate (distance up-slope and cross-slope) and the covariate distance to vegetation (only at ANP). We selected spatial variable to build our linear model (background field) with a significant p-value threshold (<0.05) for each snowpack property (response variable). The residual autocorrelation shows, with a variogram, whether the residual of the background field is stationary (random) or autocorrelated (spatial pattern) (e.g. Chilès & Delfiner, 1999). We computed a sample variogram from the residual of the linear model. From the sample variogram, we optimized the best type of variogram model and parameter to find the best variogram model, using the function *Fitted.variogram* from the *gstat* package (version 1.1-5) (RStudio, 2016).

In order to focus on vegetation distribution patterns, we created a covariate that can express the horizontal distance to the nearest island or strip of vegetation. At MAE, cross-slope distance (coordinate axis-x) expresses a horizontal distance across the slope to the nearest vegetation located on either side of the slope (Figure 13-A). At ANP, we created a covariate expressing the horizontal distance to the nearest vegetation island along each NW-SE transect (same direction as the x-coordinate) (Figure 13-B). We measured the distance to the vegetation along the transect for each SP2 profile and reset the measurement once past the vegetation island (Figure 13-B). Creating another covariate in the opposite direction along the transect created autocorrelation between covariate and overestimate the R^2 of the linear model (background field).

3.3 RESULTS

3.3.1 Meteorological conditions and snow properties spatiotemporal variability between the coastal and the valley slope

A comparative analysis of the study sites showed variability in meteorological processes and snowpack properties between the coastal slope (MAE) and the valley slope (ANP). First, we present the general meteorological conditions and highlight the variability between the study sites. Then, a cross-correlation function (CCF) was used to analysed the degree of similarity and the possible time shift (exploratory statistical analysis) for each meteorological variable. The difference in meteorological processes between the study sites could explain the difference in snowpack properties between a coastal (MAE) and a valley slope (ANP).

Weather pattern in February was dominated by high pressure cells bringing cold air masses from the Arctic. Air temperature in February was generally cold (-20 °C) with very few days with mild temperature. The temperature stays below 0 °C leading to mostly cold snow temperatures at each study sites (Figure 15). Some minor snowfall occur during this period without significant accumulation (<10 cm) (NOAA, 2018). At each site, the dominant wind direction in February comes from the northwest (Figure 14). ANP recorded the maximum wind speed in February (14 m/s), and high velocity winds (>6 m/s) were more present at ANP than MAE (Figure 14-A). These winds were associated with northwest winds (Figure 14-A). The radiation budgets were mostly below 100 W/m^2 with some days reaching 150 W/m^2, however, the ANP site recorded more radiation budget than MAE for the month of February (Figure 15-B). ANP is located in a northwest-southeast valley and high velocity wind (>3 m/s) occurs only in the direction of the valley (Figure 14-B). MAE faces the sea (north) and has a rock wall behind it (south); high velocity wind (>3 m/s) comes only from the northwest and northeast (Figure 14-B).

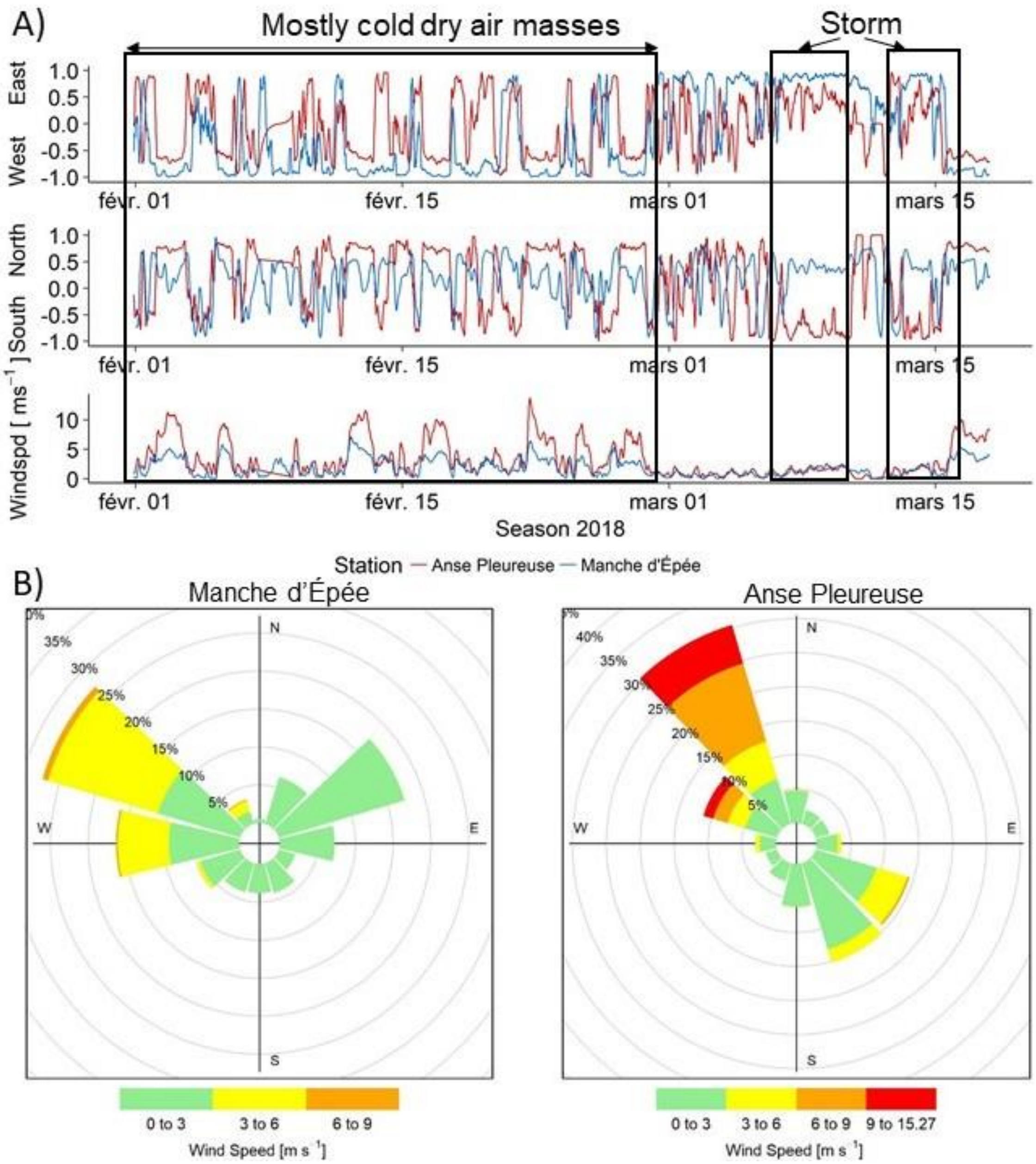


Figure 14. A) Time-series of wind direction (easting and northing component) and wind speed (m/s) from February to March 18; B) Wind direction density plot for both study sites.

March was warmer with frequent temperature close to 0 °C, with two major depressions with snow accumulation (Colorado and Hatteras lows on March 10 and 14) (NOAA, 2018). Wind direction was more variable and wind speed lower than in February (Figure 14-A). The storms brought eastern winds but different directions were recorded on our study slopes: northeast winds at MAE and southeast winds at ANP (Figure 14-A). Air temperature, radiation budget and therefore the snow temperature increased throughout March (Figure 15). However, slightly different air temperatures (warmer at ANP) and radiation budgets at the surface of the snow (higher at ANP) were recorded at the two study sites (Figure 15-A-B). This extra heat and radiation budget influenced the snow temperature profile ANP study site, which was warmer in the snowpack than MAE (Figure 15-C-D).

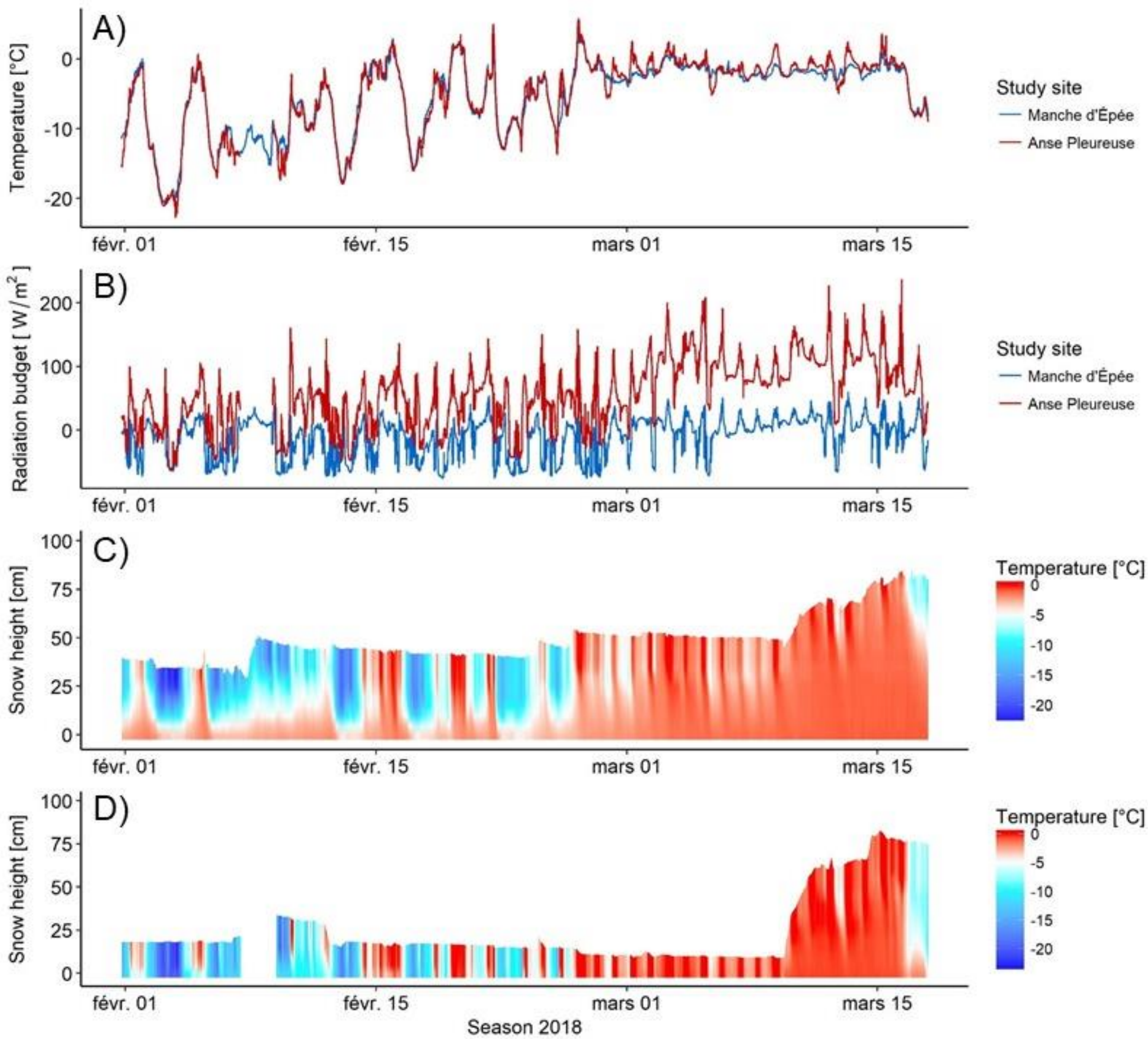


Figure 15. Meteorological data and snowpack properties recorded from February 1 to March 18, 2018, at the two study sites A) Air temperature time series. B) Radiation budget at the snow surface computed with the shortwave incident/reflected and longwave radiation incident/outgoing. C) Temperature profile at MAE. D) Temperature profile at ANP.

Linear trends were found in practically every meteorological variable after interpretation of the autocorrelation function. These trends were derived from different moving window sizes along the time series and then removed from the time series. Cross-correlation coefficients (CCF coefficient) were computed on these detrended time series for different window sizes (Figure 16). The results showed the influence on our time series of large-scale spatial (affecting both study sites in similar ways) and temporal phenomena, such as temperature rising to near 0°C throughout the winter season (weekly window size) and atmospheric circulation (daily and 2-day window sizes). These phenomena affected the overall trend of our time series and overestimated the CCF coefficient if not removed (Figure 16). As we reduced the window size and removed these large-scale spatiotemporal phenomena, CCF coefficients decreased and indicated more variability and local effect between the coastal and valley slopes.

Air temperature, relative humidity and longwave incident radiation had good similarity (maximum CCF between 0.6 and 0.8) with a negative time shift (30 min before at ANP) (Figure 16). Soil temperature was correlated with a wide range of maximum CCF coefficients (median 0.37) with three to five hours negative time shift (Figure 16). Shortwave radiation (incident and reflected) had a daily periodic component that could overestimate their CCF coefficient, if not removed. Window sizes over 24 h (24 h, two days and one week) revealed and removed a daily periodic component, resulting in low CCF coefficients and no significant time shift (Figure 16). However, the 12 h window size did not detect any daily periodic components and slightly overestimated the CCF coefficient (0.25). The CCF coefficient of the shortwave reflected (SWR) were 0.25 for every window size with no significant time shift. Wind speed had a wider range of CCF coefficients (0.8-0.4) and no significant time shift. Wind direction easting and northing were poorly correlated. The wind direction easting had a better CCF coefficient (0.3) than the northing (0.1) with a significant positive time shift (1-3 hours) (Figure 16). Wind direction and shortwave radiation were the most uncorrelated meteorological variables (Figure 16).

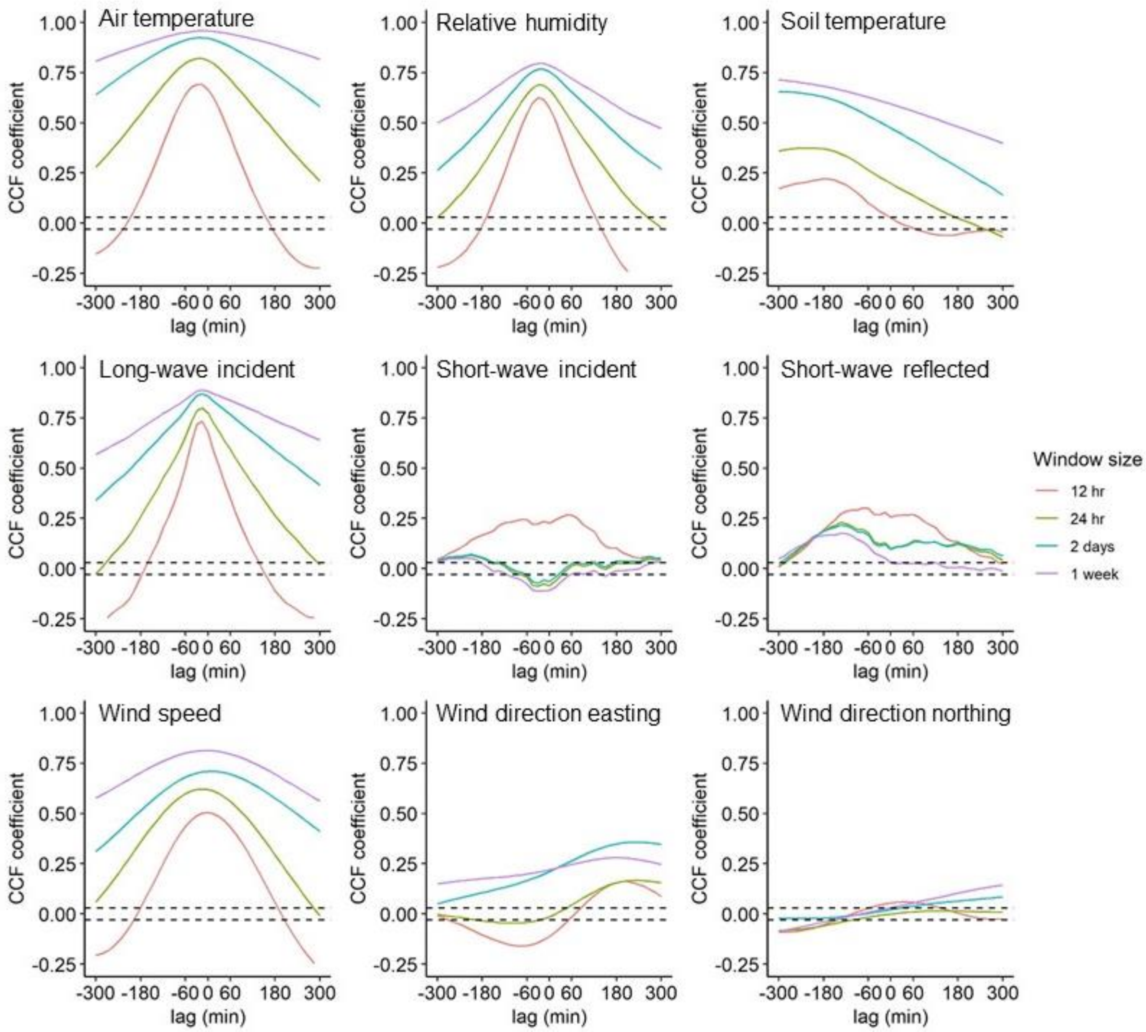


Figure 16. Result of cross-correlation function (CCF coefficient) with different window sizes to remove trend and seasonal components. Higher CCF in negative lag indicates the meteorological process occurred first at ANP; positive lag indicates it occurred first at MAE. Horizontal dashed lines indicate a 95% confidence interval.

On March 18 and 19, the upper snowpack at both study sites was characterized by several layers of decomposed and defragmented precipitation particles (DF) with variable thickness across the slopes, forming a wind slab (Figure 17). At both sites, these layers are from the same two March storm events (Figure 15). This wind slab was overlying an “old snowpack”; a combination of melt-freeze crusts and faceted crystals (FC) (Figure 17). However, this “old snowpack” was eroded down to the ground by wind in some areas of

ANP slope and thus represented only the accumulations of the two most recent storms in March (Figure 17-b). The compression test results indicated two weaknesses in the snowpack at MAE: 1) between two layers of decomposed and fragmented precipitation particles at 23 cm depth, and 2) at the bottom of the wind slab on the melt-freeze crust at 39 cm depth (Figure 17-A). The ANP site received extra heat and radiation budget (Figure 15) that affected its snow surface, creating melt-freeze crusts on top of the accumulations of both storms (Figure 17-b). The compression test results revealed only one instability at the bottom of the snowpack in decomposed and fragmented precipitation particles.

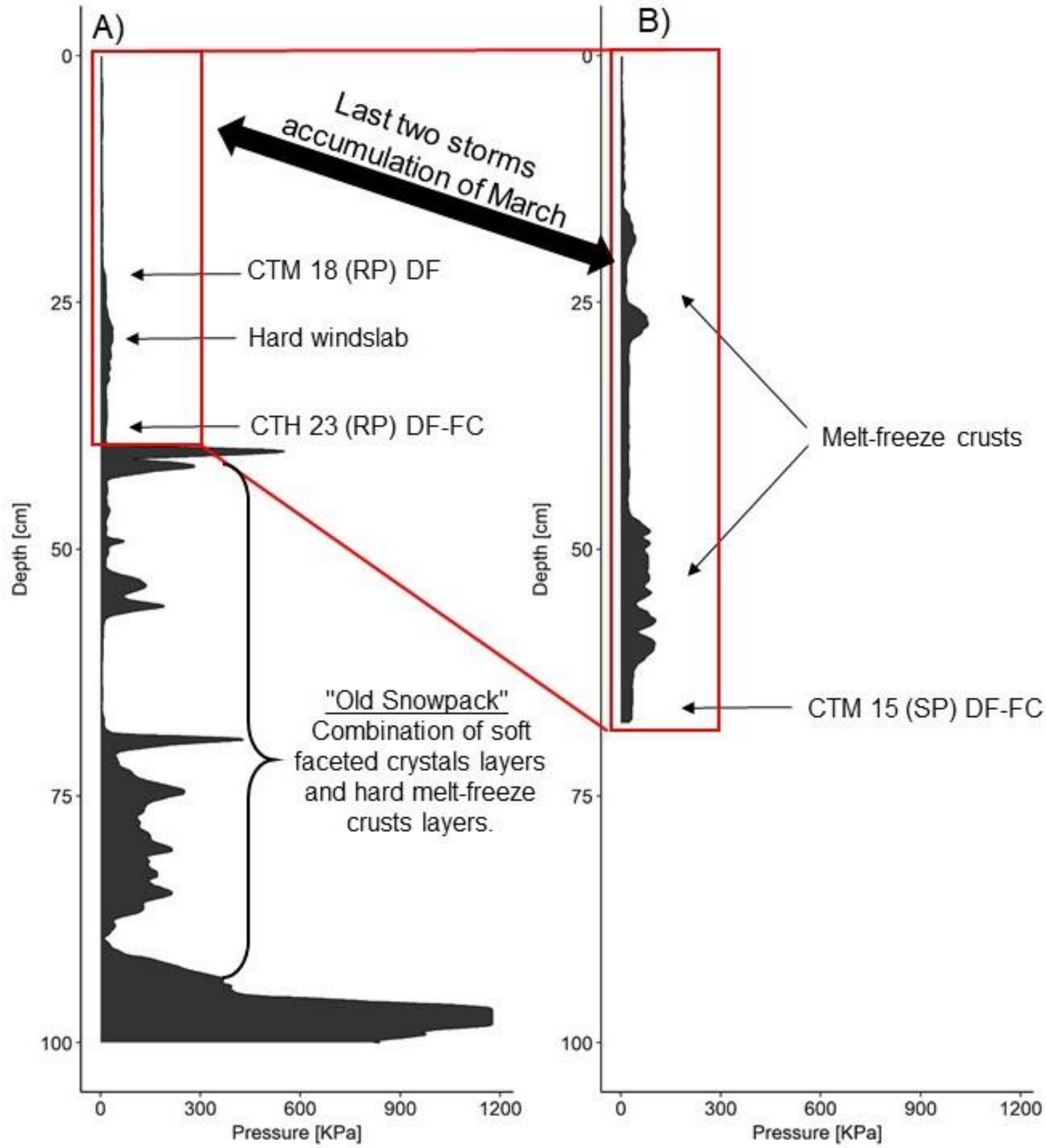


Figure 17 . Representation of SP2 profile next to the manual snow profile. Compression results are represented using Canadian Avalanche Association terminology (CAA, 2014). A) Resistance to penetration profile at MAE. B) Resistance to penetration profile at ANP.

3.3.2 Slope scale spatial variability

Spatial distribution of resistance to penetration profile

At both study sites, the resistance profile (Figure 18-Figure 19) show similar sequence of layers as presented in Figure 17. The upper snowpack is characterized by lower pressure values representing new snow deposition (Figure 18-Figure 19). The “old snowpack” is represented by a combination of higher pressure values (>150 kPa ; melt-freeze crusts) and lower values (faceted crystals) in the lower half of the snowpack (Figure 18-Figure 19). At both study sites, thicker snowpack had three sequences of high-resistance layers (melt-freeze crusts) with low-resistance layers (faceted crystals). Thinner snowpack had fewer sequences, indicating that all these crust/faceted crystals had merged together (Figure 18-Figure 19). Lower pressure values for the entire snowpack indicated that old snowpack with the melt-freeze crusts/faceted crystals sequence is absent from some areas at ANP, especially the third transect 40 m upslope (Figure 19).

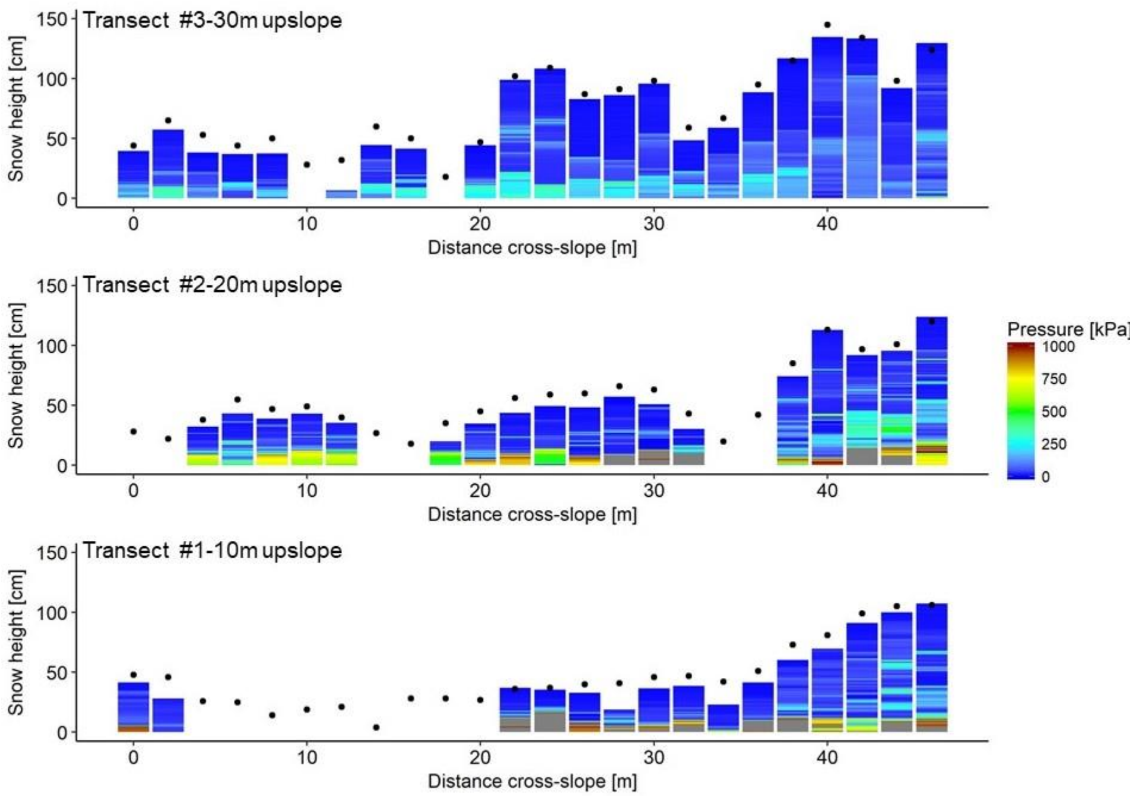


Figure 18. MAE SP2 Resistance profiles along multiples transects (1 bottom and 3 top of the slope). Snowpack less than 30 cm could not be detected by the SP2 probe. Black dots are the median snow heights of the three profiles observed on the graduated SP2 snowprobe. Grey colour corresponds to pressure over 1000 kPa and could represent hard melt-freeze crust or the ground.

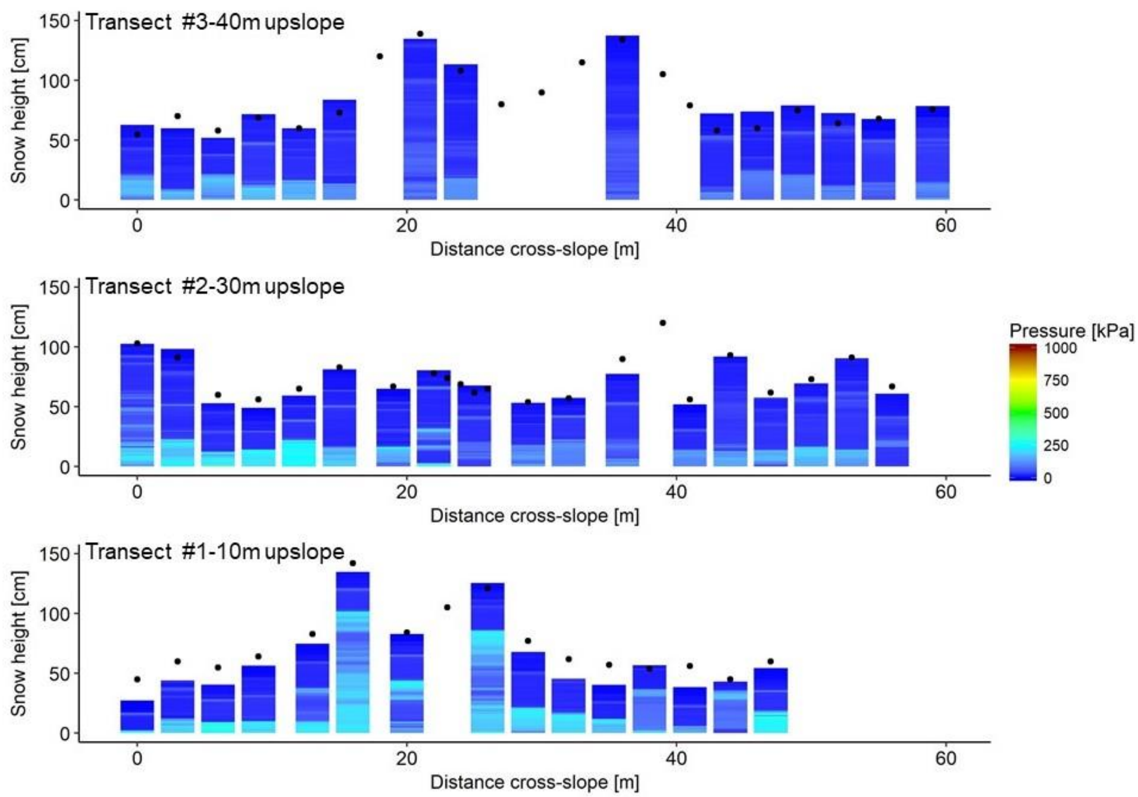


Figure 19. ANP SP2 resistance profiles along multiple transects (1 bottom and 3 top of the slope). Snowpack less than 30 cm could not be detected by the SP2 probe (blank area) but snow height was measured. Black dots show median snow heights of the three profiles observed on the graduated SP2 snowprobe. Grey colour corresponds to pressure over 1000 kPa and could represent hard melt-freeze crust or the ground.

3.3.3 Geostatistical analysis

Background field

The first step was to develop a linear model for the three main snowpack properties: snow height, slab thickness and slab mean resistance. The results of the geostatistical analysis are presented in Table 7. At MAE, a thicker snowpack was observed near the right top area (west) of the slope, close to the vegetation strip (Figure 18). The cross- and up-slope distances were significant variables in the linear regression model and could explain 61 % of the snow height variance (R^2=0.61) (Table 7). The composition of the linear slab thickness model was nearly the same as the snow height, with distance up- and cross-slope being significant, but it explained only 26 % of the slab thickness variance. The linear model for the slab mean resistance had only the distance up-slope being significant (p-value <0.05) with 22 % of variance explained (Table 7).

At ANP, snow accumulation was more sparsely distributed (Figure 19) and up- and cross-slope distances were not significant (Table 7). However, the covariate distance to vegetation (log) was significant even if the linear model only explained 21 % of the variance. For the slab thickness, distance up- and cross-slope were the only significant spatial variables in the spatial model and distance to vegetation was not significant. The linear model explained 33 % of the slab thickness variance at ANP. For the slab mean resistance, only distance cross-slope composed the linear model with an R^2 of 0.19 (Table 7).

In almost all cases, the linear regression models explain small percentages of the variance (20-30 %) except for the snow height at MAE (61 %). The linear models for snow height and slab mean resistance are constituted of different spatial variables (Table 7). However, the spatial variables used in the linear model for slab thickness were the same (coordinate) at both study sites.

Table 7 . Results of linear model and Variogram for three snowpack properties: Snow height, slab thickness and slab mean resistance.

	Spatial model					Variogram				
	Estimate	STD. Error	t-value	p-value	R^2	Formula	Nugget	Sill	Range	Model
MAE/Snow height										
Distance up-slope	15.1	2.95	5.11	<0.05*	0.61	up/cross-slope	0	41178	7.00	Spherical
Distance cross-slope	16.45	1.74	9.44	<0.05*						
Anse Pleureuse/Snow height										
Distance up-slope	0.86	2.41	0.36	0.72	0.21	dist. veg (log)	0	45639	8.37	Spherical
Distance cross-slope	2.05	1.79	1.15	0.25						
Dist. to vegetation(log)	-266.08	64.91	-4.01	<0.05*						
MAE/Slab thickness										
Distance up-slope	6.13	2.13	2.88	<0.05*	0.26	up/cross-slope	11302	15442	10.22	Spherical
Distance cross-slope	4.76	1.12	4.08	<0.05*						
Anse Pleureuse/Slab thickness										
Distance up-slope	11.41	2.53	4.52	<0.05*	0.33	up/cross-slope	11702	49577	12.65	Spherical
Distance cross-slope	4.07	1.92	2.12	0.04*						
Dist. to vegetation(log)	-72.59	84.62	-0.86	0.39						
MAE/Slab mean resistance										
Distance up-slope	-0.73	0.17	-4.16	<0.05*	0.22	up-slope	-	-	-	pure nugget
Distance cross-slope	0.03	0.09	0.39	0.7						
Anse Pleureuse/Slab mean resistance										
Distance up-slope	0.25	0.15	1.59	0.12	0.19	cross-slope	-	-	-	pure nugget
Distance cross-slope	0.27	0.12	2.3	0.02*						
Dist. to vegetation(log)	6.12	5.17	1.19	0.24						

* p-value < 0.05

We modelled a variogram using the residual of the linear model to describe the residual spatial pattern not currently explained by the linear model (Table 7). Each modelled variogram is the same (spherical or nugget) between study sites for the same snowpack properties, but with different parameters (Table 7 and Figure 20). The modelled snow height variograms have no nugget (non-spatial variance), similar sill values (near 40,000) and similar range around 7-8 m. The modelled slab thickness variograms are also similar, with the nugget (around 11,000) and the range around 10 to 12 m, but the sill (spatial variance) is different at 15,44 for MAE and 49,57 for ANP (Table 7). This indicates that non-spatial variance and range of the spatial pattern are the same for both study sites but the residual slab thickness spatial variance (sill) is more significant at ANP (Figure 20). For slab mean resistance, the model variogram produced pure random nugget effect at both study sites, indicating a spatially random process or too much variability in the SP2 resistance measurement. Both ANP variograms exhibited a hole effect around 25 m and showed horizontal spatial cyclicity.

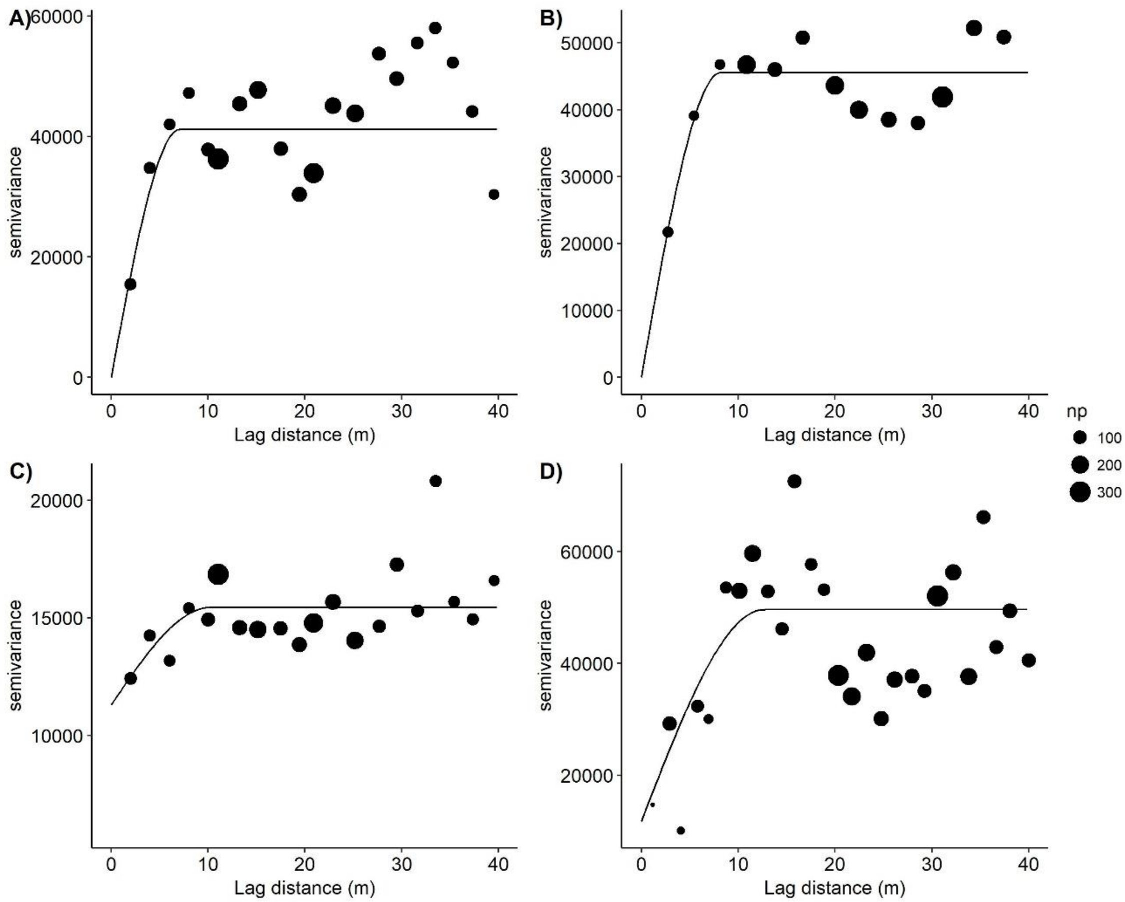


Figure 20. Sample variogram and model variogram. Y-axis may differ between variogram A) Variogram of the snow height at MAE. B) Variogram of the snow height spatial model at ANP. C) Variogram of the slab thickness spatial model at MAE. D) Variogram of the slab thickness spatial model at ANP. NP represent the number of pair of lags (pairs of observations).

3.4 DISCUSSION

3.4.1 Meteorological and snowpack spatiotemporal variability

Between the coastal and the valley slope

Wind direction is highly influenced by the surrounding topography. MAE faces the sea (north) and has a rock wall behind it (south). Consequently, high velocity wind (>3 m/s) comes only from the northwest and northeast (Figure 14-B). The rock wall over the slope limits the south winds and tends to enhance east-west-north component winds. The topography's impact on the wind regime indicates the snow accumulation/transport process is influenced by two directions: northwest and northeast. The maximum wind velocities are linked to wind from the northwest and could also be attributed to snow erosion (Figure 14-18). Northeast winds are associated with snowstorms and snow accumulation. The MAE slope is concave in top view could also explain why it is more protected from wind Figure 15 also shows lower radiation budget on the coastal slope in comparison to the valley slope, resulting in the creation of different snow layers. At the valley site, snow crystals remain dry and create a combination of hard and soft wind slabs (defragmented precipitation particles). The results of the compression test show two weak interfaces: one between hard and soft wind slabs and the second between the entire wind slab (upper snowpack) and a crust (old snowpack) (Figure 17-a).

At ANP, high velocity winds (>3 m/s) were from only two directions, which represent the axis of the valley (NW-SE). The wind is channelled into the valley thus promoting northwest and southeast component winds. It also enhances the venturi effect when strong dominant winds enter the valley from the northwest, increasing wind velocities in comparison to the coastal slope. Southeast, the second most dominant wind direction, could be linked to March snowstorms and snow accumulation. However, in February, snow height was lower at ANP, which could indicate more wind erosion at the valley site. Compared to the MAE concave slope, the ANP slope is convex in top view and could explain more exposition to wind. This difference in snow height will affect the overall snow temperature profile and ultimately snow metamorphism, especially at the base of the snowpack if the snowpack is not important enough to isolate the base from air temperature. The ANP site received extra heat and radiation (Figure 15) and this radiation budget affected its snow surface, creating two melt-freeze crusts at the bottom of both storm accumulations (Figure 17-b). This created two strong layers, increasing the snow strength of the slab and preventing fracture into the lower weak layer. However, this weak interface between the new snow and the old snowpack (crust or ground) remained weak, as demonstrated by the compression test results (Figure 17-b).

Results from the cross-correlation analysis show the greatest difference in the wind regime and radiation budget between the north-facing slope along the coast and the southwest-facing slope in the valley (Figure 16). The wind regime (speed and direction) can explain different snow accumulation (overall snowpack or storm accumulation) patterns on the slope. Wind velocities are higher in the valley and could explain the higher snow ablation in the valley compared to the coast. The wind regime from the northwest (> 7 m/s) is enough to initiate snow transport and cause snow ablation (e.g. Li & Pomeroy, 1997). However, the study slope along the coast is more protected from the wind than its neighbouring coastal slopes, where snow ablation could be more significant (shape of the slope in top view). Wind regimes with east components (northeast for the coast and southeast for the valley) are attributed to snowstorms (only two Hatteras lows) with lower maximum wind velocities (3-6 m/s) than the dominant northwest wind (> 7 m/s). The second wind regime result in snow accumulation for both study areas. Wind direction is perpendicular to the slope aspect, causing cross-loading. Snow accumulation patterns over the slope are different, but the types of observed instabilities (weak interface between storm accumulation) are the same for both areas (Figure 17). These observations support the results of Gauthier *et al.* (2017), which found that snow precipitation over two/three days was a significant variable to predict avalanche formation for avalanche slope along provincial roads 132 (coast) and 198 (valley). However, snow precipitation over two days and wind speed were the most significant meteorological variables to explain snow avalanches along the provincial road 132 (coast) and snow precipitation over three days in the valley of ANP (Gauthier *et al.*, 2017). This delay in significant snow accumulation predicting avalanches could be explained by the radiation budget differences that cause different slab snow strengths. This assumption could be more emphasized in future research.

Vegetation effects on snowpack spatial variability

Spatial models created with geostatistical analysis provide information on the main spatial patterns of snow height and slab thickness. Snow height is the product of every snow accumulation and ablation event in the season. Spatial patterns of snow height could be linked to strong northwest wind causing snow redistribution and ablation, but also north/southeast wind during March snowstorms causing redistribution and accumulation throughout the season. However, slab thickness was mostly the product of the last two snowstorms with north/southeast wind. The spatial pattern of slab thickness indicated that only snow accumulation processes cause the last March's snowstorm (Hatteras lows). Analysis of spatial model and residual spatial pattern could be linked to these two different wind regimes.

At the coastal site, the snow height spatial model was defined by its coordinates and showed that the overall snowpack was deeper near vegetation in the right top corner of the slope. Snowpack in this area is protected from northwest wind by forest (Figure 21). At the valley site, the snow height spatial model was not defined by its coordinates but rather by the covariate distance to vegetation. Snowpack was also protected from northwest wind by vegetation, but this area is located in the middle of the slope where most vegetation is located (Figure 21). The spatial model for slab thickness at the coast site was the same as for snow height but the regression coefficient of the slab thickness spatial model was nearly half that of the snow height spatial model. R^2 was also lower, with 0.26 for slab thickness and 0.61 for snow height. There was less accumulation on the right side of the slope during storms than wind snow deflation events. At the valley site, the spatial model for slab thickness was located at the top right corner of the slope. Snow accumulation was located in front of vegetation exposed to the southeast wind and closer to the base of the rock wall (top of the slope) (Figure 21).

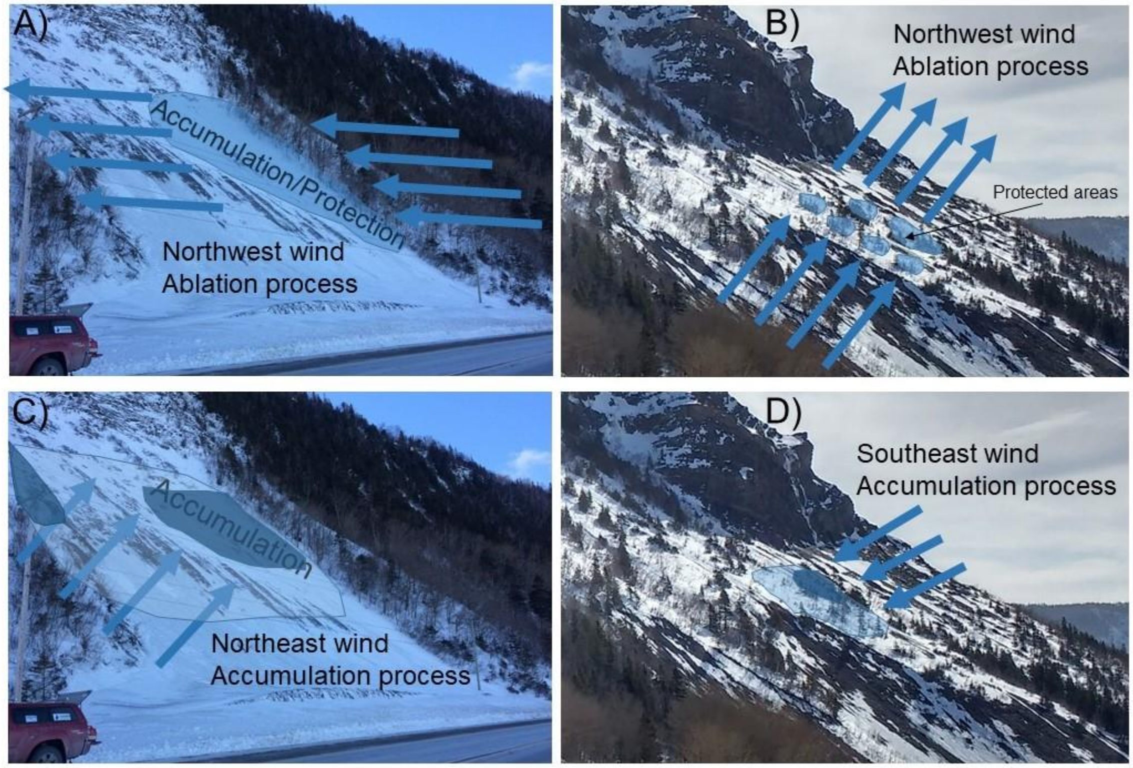


Figure 21 . Conceptual spatial snow accumulation/ablation pattern for the two dominant wind directions. Snow ablation spatial pattern associated with cold dry high pressure and strong northwest wind: A) MAE (coastal site), B) ANP (valley site). Snow accumulation spatial pattern associated with low pressure cells (Hatteras lows) and northeast wind for MAE (C) and southeast wind for ANP (D). Photos were taken in February 2018 during strong wind snow ablation process.

Variogram analysis on the residual of these spatial models indicates if any spatial pattern remains. It shows characteristics of residual spatial patterns but no evidence for a potential explanation. However, hypotheses can be induced by these characteristics for the snow height and slab thickness variogram model (Figure 20). The range, from around 8 to 20 m, was similar to other studies on spatial variability (Bellaire & Schweizer, 2011; Lutz *et al.*, 2007; Reuter *et al.*, 2016; Schweizer & Reuter, 2015). The snow height variogram models are similar for both of our study sites and could be explained by similar spatial process. This spatial process could be the complex interaction (turbulence) with the northwest wind and the microtopography (surface and vegetation). For slab thickness, residual spatial patterns are also similar but show a greater range than snow height (Table 7). Complex interaction with the microtopography could also be responsible but with a different wind regime (snowstorm with east component). Both ANP variograms exhibit hole effect around 20 m, which indicates horizontal (variogram direction) spatial cyclic features (Pyrcz & Deutsch, 2003). The cause of this cyclicity could be the sparse vegetation distribution at ANP, which range around 20 m, but this hypothesis should be further analyzed in future research. It also indicates that the covariate distance to vegetation did not fully describe the snow/vegetation interaction.

3.4.2 Snow avalanche hazard management

The valley site had more radiation budget (short and longwave radiation) than the coast site, and this difference increased through the season (Figure 15). This radiation budget affected snow temperature in the upper snowpack, which was closer to 0°C in March at the valley site (Figure 15). This warmer snowpack created two small melt-freeze crusts in the slab, thereby increasing slab snow strength. This melt-freeze crust does not influence weak layer properties but should increase slab snow strength and should take more loading to cause avalanche formation. This might explain why more snow precipitation is needed on the ANP slope before snow avalanches are triggered. However, both study sites had nearly the same weak layer, a weakly bonded interface between the upper wind slab and the old snowpack (crust or ground). Spatial variability in slab properties was also explained by the variability of snow deposition and radiation budget in the Swiss alps (Reuter *et al.*, 2016). For avalanche forecasting and road management, ANP (valley) could avalanche after MAE (coast) during cold/dry snowstorms, but the timing need to be clarify further data and analysis. This useful information should help the forecasters when issuing avalanche risk assessments for provincial roads 132 and 198. It could also help forecasters and road managers time road closures or other risk road management options.

Locating snow accumulation areas on these small avalanche-prone slopes can be used improve avalanche control and mitigation efficiency. The position of the existing mitigation system could be adapted to protect the road in these snow accumulation areas. These earth mounds barriers, located between the road and the base of the slope, provide a buffer where snow and rock can accumulate. In some locations, this mitigation system is not being maintained near slopes with the greatest snow accumulations. These findings should be helpful when planning future avalanche mitigation systems such as snow fencing and help to reduce costs by targeting snow accumulation areas. They could also help forecasters designing avalanche control systems to select potential avalanche trigger areas for Remote Avalanche Control System (RACS) implementation or hand charging of explosives.

3.4.3 Data quality and reliability for snowpack spatial variability assessment

This study has several spatial and temporal limitations. First, the data analyzed to compare valley and coastal slopes represented only two slopes and two months of the winter season, specifically before, during and after two major depressions (Hatteras and Colorado low). Also, the slope selected at MAE is the same aspect as his neighbouring slope, but less expose to wind. The MAE slope is concave in top view compared to convex for his neighbouring slope. We choose this slope because it allowed snow measurement to be taken throughout the season; while neighbouring slopes seems to get similar snow accumulation in snowstorms, it gets blown off in the presence of strong northwest winds (e.g. B. Hétu & Vandelac, 1989). At ANP, the slope is convex in top view and could explain the wind exposure more prominent at ANP (Figure 15). The locations of the snow temperature strings and snow height sensors induced a certain limitation in our results. At ANP in particular, snow height around the station was variable and could have affected the snow temperature profile if the string was positioned at a different location near the station.

The main SP2 limitation was the snow depth estimation for each resistance measurement, which caused considerable error in the vertical positioning of layers (Hagenmuller *et al.*, 2018). To overcome this limitation, we used the Hagenmuller & Pilloix (2016) matching algorithm to reduce the variability of the SP2 measurement. However, the variogram analysis shows considerable non-spatial variance (nugget) for the two snowpack properties derived from SP2 profile. This nugget could represent residual variability from the SP2 measurement, even after using the matching algorithm. These results show the usefulness of the SP2 to track down layers in space but other measurements (e.g resistance) are limited by probe accuracy (Hagenmuller *et al.*, 2018).

Geostatistical analysis can be used to estimate the spatial variability of some snowpack properties related to snow instabilities. However, true measurements of snow instability parameters need a more precise penetrometer to derive metrics of instability: failure initiation, crack propagation criteria and slab tensile support (Reuter & Schweizer, 2018). The sample variogram also shows the limitations of our snow sampling design, which only assesses horizontal variability. Our results show that vertical variability was also important; our snow sampling assessed vertical variability at 10 m minimum spacing, compared to two meters for horizontal variability. Other studies have used different snow sampling designs but produced results similar to ours, with a range of around 8 m to 26 m (Bellaire & Schweizer, 2011; Lutz *et al.*, 2007; Reuter *et al.*, 2016; Schweizer & Reuter, 2015). Low R^2 coefficients of the linear spatial models indicate residual variance (spatial patterns) were important. In addition to linear regression, other types of spatial regression should also be tested to assess different types of spatial relationships. Also, more covariates should be included in future studies to test the influence of microtopography.

3.5 CONCLUSION

This study highlighted the variability between avalanche-prone valley and coastal slopes. We found that air temperature, relative humidity, longwave radiation and wind speed were relatively similar over different temporal scales. However, wind direction and shortwave radiation were uncorrelated and influenced by local factors mainly exposure, attributed to the coastal and valley slopes. This variability in meteorological processes was linked to variability in snowpack properties between the coastal and the valley slopes. Two different wind regimes were described that are strongly influenced by terrain specific to a valley or coastal environment. We found that snow stratigraphy was similar between the study sites but slab snow strength was greater at the valley site due to higher radiation heat gains to the snowpack throughout the season. However, these findings only represent one season for a particular type of cold/dry snowstorm (Hatteras lows). Snow cover modelling should be incorporated into future studies on coastal and low elevation valley avalanche slopes to further links the meteorological processes and their influence on spatial variability of snowpack properties.

Two particular spatial patterns of snow ablation and accumulation were linked to the interaction between two specific wind regimes and the distribution of vegetation. Strong northwest wind causes snow ablation and creates locally-protected snow accumulation areas behind vegetation (trees and bushes) facing into the dominant wind. Snowstorms (Hatteras lows) usually bring eastern wind, causing snow accumulation on the entire slope but especially in front of vegetation, against the wind direction. Snow accumulation was also more present towards the top of the slope. More advanced spatial modelling (hierarchal and non-linear spatial relationship) should be explored in future studies to improve spatial prediction and further the understanding of the spatial variability of snowpack properties and snow instability. A better characterisation of the microtopography such as land use, terrain shape (e.g. convex roll) or vegetation/canopy should be integrated into spatial modelling as covariates. This could improve our understanding and provide more accurate spatial predictions of the possible trigger locations or weak zones in the snowpack to help recreationists, forecasters and guides to assess the snowpack stability.

We also discussed another important outcome, improvements to the avalanche forecasting and mitigation program for provincial roads 132 and 198. The timing of potential dry snow avalanches was discussed and the results of Gauthier *et al.* (2017), who observed a delay for dry snow avalanche during snowstorms at ANP (valley site), were validated. At the slope scale, determining snow accumulation pattern locations will also improve the efficiency of avalanche forecasting and mitigation programs.

3.6 ACKNOWLEDGEMENT

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CONCLUSION GÉNÉRALE

Cette recherche a documenté, à plusieurs échelles spatiotemporelles, les propriétés du manteau neigeux pour les deux secteurs de prévision d'Avalanche Québec. Malgré certaines différences entre les deux secteurs, le climat de neige de type *rainy continental* proposé par Ikeda *et al.* (2009), peut caractériser le climat de neige du nord de la péninsule gaspésienne. Une comparaison globale avec les climats de neige classique (continental, transition et maritime), a permis de mieux cerner le caractère spécifique du climat de neige gaspésien. Cette comparaison a également permis d'établir une ressemblance avec les Alpes japonaises et le Mont Washington, et de définir ces trois régions en tant que climat de neige *rainy continental*, tel que Ikeda *et al.* (2009) le proposent. Cependant, nous pensons que le climat de neige proposé ne constitue pas un quatrième type de climat de neige, mais plutôt une autre déclinaison du climat de neige de type Transition. Celui-ci devra donc être élargi pour d'autres régions où les influences maritimes et continentales sont présentes, mais sont différentes que celles observées dans l'ouest de l'Amérique du Nord tel que décrit dans la littérature (e.g. Haegeli & McClung, 2007; Mock & Birkeland, 2000). L'intégration des données de prévision des avalanches permet de valider les données de manteaux neigeux et météorologiques. Cependant, cette étude a seulement utilisé une partie des données de prévision (type de problème d'avalanche) en tenant compte de leur fréquence d'utilisation, mais n'a pas été couplée avec le danger d'avalanche complet (probabilité de déclenchement et taille probable) tel que Statham *et al.* (2018) le propose. Shandro & Haegeli (2018) ont intégré l'ensemble des données de prévision qui définit le danger d'avalanche (type de problème d'avalanche, probabilité de déclenchement et taille probable d'une avalanche) pour caractériser le danger d'avalanche de l'Ouest canadien. Ce type d'analyse est intéressant, mais est seulement réalisable pour des régions où des systèmes de prévision des avalanches sont opérationnels depuis de nombreuses années pour constituer une base de données. Pour de nouvelles régions où ces bases de données sont inexistantes ou insuffisantes, l'utilisation de modèles de couverture de neige (e.g. SNOWPACK) pourrait être intéressante pour constituer des bases de données sur les propriétés de neige dans des régions où le climat de neige n'a pas été défini (Mock *et al.*, 2017).

Cette étude a également montré le lien entre la variabilité spatiotemporelle des processus météorologiques et des propriétés du manteau neigeux pour un versant côtier et un versant situé dans une vallée en basse altitude. La variabilité du régime de vent (direction et vitesse) et du bilan radiatif de surface explique en partie la variabilité des propriétés du manteau neigeux, plus précisément les propriétés mécaniques de la plaque plutôt que de la couche faible susceptible de former une avalanche. De plus, la variabilité entre ces deux versants ne peut pas être représentée uniquement par une station météorologique de référence en vallée, utilisée pour la prévision des avalanches. L'intégration de modèles de couvert de neige pourrait améliorer la prévision des avalanches sur ces versants, qui devrait tenir compte de la variabilité des processus météorologiques et des propriétés de neige. À l'échelle de la pente, la distribution de la végétation influence la distribution spatiale de l'accumulation totale du manteau neigeux et également de l'accumulation des tempêtes (superficielle). Ces résultats devraient aider à améliorer la prévision des avalanches sur ces versants, mais également les futurs systèmes d'atténuation, d'infrastructures de protection et de contrôle des avalanches de neige (e.g. contrôle par explosifs ou clôtures à neige).

Les variables indépendantes dans la modélisation spatiale ne sont pas des mesures directes de la stabilité. Ces paramètres d'instabilité pourraient être acquis à partir d'un pénétromètre haute-résolution et permettre la modélisation spatiale de cette instabilité (e.g. Reuter *et al.*, 2016). L'influence de la végétation a été partiellement démontrée, mais des techniques avancées de modélisation ainsi que d'acquisition de données géospatiales (photogrammétrie par drone) pourraient permettre une meilleure caractérisation et une modélisation de l'influence de la végétation sur les propriétés du manteau neigeux. Ces techniques pourraient également permettre d'inclure d'autres caractéristiques microtopographiques à la modélisation comme la forme de la pente (e.g. convexité/concavité), la hauteur et la proximité des arbres ainsi que des affleurements rocheux. L'inclusion de ces paramètres microtopographiques pourrait refléter l'interaction des processus micrométéorologiques avec la microtopographie. Cette technique a été utilisée abondamment où l'utilisation des paramètres topographiques en modélisation spatiale reflète des processus météorologiques en interaction avec la topographie «process-based terrain correlation» (Hägeli & McClung, 2003). L'inclusion future de la microtopographie dans la modélisation spatiale pourrait permettre de mieux comprendre la variabilité spatiale à l'échelle d'une pente non uniforme pour identifier les pièges naturels présents sur des pentes situées en terrain complexe (e.g. couloirs, falaises rocheuses).

RÉFÉRENCES BIBLIOGRAPHIQUES

Armstrong, R. L., & Armstrong, B. R. (1987). Snow and avalanche climates of the western United States: a comparison of maritime, intermountain and continental conditions. *IAHS publication*, *162*, 281-294.

Avatech. (2016). SP2 owner's manuel. Consulted at http://process.monitorering.no/measureit/files/pdf_datablad/avatech/avatech_sp2_manual.pdf

Barry, R. G. (2008). *Mountain weather and climate* (3rd). Cambridge: Cambridge University Press.

Bellaire, S., & Schweizer, J. (2011). Measuring spatial variations of weak layer and slab properties with regard to snow slope stability. *Cold Regions Science and Technology*, *65*(2), 234-241.

Birkeland, K. (2001). Spatial patterns of snow stability throughout a small mountain range. *Journal of Glaciology*, *47*(157), 176-186.

Borish, M., Birkeland, K. W., Custer, S., Challender, S., & Hendrikx, J. (2012). *Surface hoar distribution at the scale of a helicopter skiing operation*. Communication présentée au International Snow Science Workshop, Anchorage, Alaska.

Boucher, D., Filion, L., & Hétu, B. (2003). Reconstitution dendrochronologique et fréquence des grosses avalanches de neige dans un couloir subalpin du mont Hog's Back, en Gaspésie centrale (Québec). *Géographie physique et Quaternaire*, *57*(2-3), 159-168.

Boucher, D., & Hétu, B. (2009). *La 'mort blanche'au Québec (Canada) depuis 1825: de la prise de conscience du problème à la gestion du risque*. Communication présentée au International Snow Science Workshop., Davos, Switzerland.

CAA. (2014). *Observation guidelines and recording standards for weather, snowpack and avalanches*. Revelstoke, British-Columbia: Canadian Avalanche Association.

Campbell, C., & Jamieson, B. (2007). Spatial variability of slab stability and fracture characteristics within avalanche start zones. *Cold Regions Science and Technology*, *47*(1-2), 134-147.

Canada, E. (2010). Canadian climate normals 1981-2010 station data [on line]. Consulted july 2019, at http://climate.weather.gc.ca/climate_normals/index_e.html.

Chatfield, C. (2004). *The analysis of time series: an introduction*. Boca Raton, Florida: CRC press.

Chilès, J., & Delfiner, P. (1999). *Geostatistics: Modeling spatial uncertainty*. New York: John Wiley Son.

Colbeck, S., & Jamieson, J. (2006). *Surface hoar growth from valley cloud*. Communication présentée au International Snow Science Workshop, Telluride, Colorado.

Deems, J. S., Fassnacht, S. R., & Elder, K. J. (2006). Fractal distribution of snow depth from LiDAR data. *Journal of Hydrometeorology*, *7*(2), 285-297.

Dubé, S., Filion, L., & Hétu, B. (2004). Tree-Ring Reconstruction of High-Magnitude Snow Avalanches in the Northern Gaspé Peninsula, Québec, Canada. *Arctic, Antarctic, and Alpine Research*, *36*(4), 541-550.

Eckerstorfer, M., & Christiansen, H. H. (2011). The "High Arctic maritime snow climate" in central Svalbard. *Arctic, Antarctic, and Alpine Research 43*(1), 11-21.

Eckerstorfer, M., Farnsworth, W. R., & Birkeland, K. W. (2014). Potential dry slab avalanche trigger zones on wind-affected slopes in central Svalbard. *Cold Regions Science and Technology*, *99*, 66-77.

Elder, K., Dozier, J., & Michaelsen, J. (1991). Snow accumulation and distribution in an alpine watershed. *Water Resources Research*, *27*(7), 1541-1552.

Erickson, T. A., Williams, M. W., & Winstral, A. (2005). Persistence of topographic controls on the spatial distribution of snow in rugged mountain terrain, Colorado, United States. *Water Resources Research*, *41*(4).

Feick, S., Kronholm, K., & Schweizer, J. (2007). Field observations on spatial variability of surface hoar at the basin scale. *Journal of Geophysical Research: Earth Surface*, *112*(F2).

Fortin, G., & Hétu, B. (2009). Les extrêmes météorologiques hivernaux et leurs impacts sur la couverture neigeuse dans les monts Chic-Chocs, Gaspésie, Québec. *Geographia Technica, numéro spécial*, 181-186.

Fortin, G., & Hétu, B. (2010). *Variabilité de l'épaisseur, de l'équivalent en eau et de la densité de la neige dans les monts Chic-Chocs en Gaspésie (1980-2009)*. Communication présentée au Association Internationale de Climatologie

Fortin, G., & Hétu, B. (2013). Estimating winter trends in climatic variables in the Chic-Chocs Mountains, Canada (1970–2009). *International Journal of Climatology*.

Fortin, G., Hétu, B., & Germain, D. (2011). Climat hivernal et régimes avalancheux dans les corridors routiers de la Gaspésie septentrionale (Québec. Canada). *Climatologie*, *8*, 9-25.

Gagnon, R. M. (1970). *Climat des Chic-Chocs. Ministère des Richesses naturelles, Québec, MP 36*.

Gaume, J., Schweizer, J., Herwijnen, A., Chambon, G., Reuter, B., Eckert, N., & Naaim, M. (2014). Evaluation of slope stability with respect to snowpack spatial variability. *Journal of Geophysical Research: Earth Surface*, *119*(9), 1783-1799.

Gaume, J., Van Herwijnen, A., Chambon, G., Wever, N., & Schweizer, J. (2017). Snow fracture in relation to slab avalanche release: critical state for the onset of crack propagation. *The Cryosphere*, *11*(1), 217-228.

Gauthier, F., Germain, D., & Hétu, B. (2017). Logistic models as a forecasting tool for snow avalanches in a cold maritime climate: northern Gaspésie, Québec, Canada. *Natural Hazards*, *89*(1), 201-232.

Gauthier, F., Hétu, B., & Bergeron, N. (2012). Analyses statistiques des conditions climatiques propices aux chutes de blocs de glace dans les corridors routiers du nord de la Gaspésie, Québec, Canada. *Canadian Geotechnical Journal*, *49*(12), 1408-1426.

Germain, D., Filion, L., & Hetu, B. (2009). Snow avalanche regime and climatic conditions in the Chic-Choc Range, eastern Canada. *Climatic Change*, *92*(1-2), 141-167. doi: 10.1007/s10584-008-9439-4

Germain, D., Hétu, B., & Filion, L. (2010). Tree-Ring Based Reconstruction of Past Snow Avalanche Events and Risk Assessment in Northern Gaspé Peninsula (Québec, Canada). Dans M. Stoffel, M. Bollschweiler, D. R. Butler, & B. H. Luckman (Éds.), *Tree Rings and Natural Hazards* (Vol. 41, pp. 51-73): Springer Netherlands. doi: 10.1007/978-90-481-8736-2_5

Goela, P. C., Cordeiro, C., Danchenko, S., Icely, J., Cristina, S., & Newton, A. (2016). Time series analysis of data for sea surface temperature and upwelling components from the southwest coast of Portugal. *Journal of Marine Systems*, *163*, 12-22.

Graveline, M.-H., & Germain, D. (2016). Ice-block fall and snow avalanche hazards in northern Gaspésie (eastern Canada): Triggering weather scenarios and process interactions. *Cold Regions Science and Technology*, *123*, 81-90.

Gray, J., Davesne, G., Fortier, D., & Godin, E. (2017). The Thermal Regime of Mountain Permafrost at the Summit of Mont Jacques-Cartier in the Gaspé Peninsula, Québec, Canada: A 37 Year Record of Fluctuations showing an Overall Warming Trend. *Permafrost and Periglacial Processes*, *28*(1), 266-274.

Grunewald, T., Stotter, J., Pomeroy, J., Dadic, R., Baños, I. M., Marturià, J., ... Lehnig, M. (2013). Statistical modelling of the snow depth distribution in open alpine terrain. *Hydrology and Earth System Sciences*, *17*, 3005-3021.

Guy, Z. M., & Birkeland, K. W. (2013). Relating complex terrain to potential avalanche trigger locations. *Cold Regions Science and Technology*, *86*, 1-13.

Haegeli, P., Atkins, R., & Klassen, K. (2010). *Auxiliary material for Decision making in avalanche terrain: a field book for winter backcountry users*. Revelstoke, BC, Canada: Canadian Avalanche Center.

Haegeli, P., & McClung, D. M. (2007). Expanding the snow-climate classification with avalanche-relevant information: initial description of avalanche winter regimes for southwestern Canada. *Journal of Glaciology*, *53*(181), 266-276.

Hägeli, P., & McClung, D. M. (2003). Avalanche characteristics of a transitional snow climate—Columbia Mountains, British Columbia, Canada. *Cold Regions Science and Technology*, *37*(3), 255-276.

Hägeli, P., & McClung, D. M. (2004). Hierarchy theory as a conceptual framework for scale issues in avalanche forecast modeling. *Annals of Glaciology*, *38*, 209-214.

Hagenmuller, P., Pielmeier, C., & Marshall, H.-P. (2018). Evaluation of the snow penetrometer Avatech SP2. *Cold Regions Science and Technology*, *149*, 83-94.

Hagenmuller, P., & Pilloix, T. (2016). A new method for comparing and matching snow profiles, application for profiles measured by penetrometers. *Frontiers in Earth Science*, *4*, 52.

Harper, J. T., & Bradford, J. H. (2003). Snow stratigraphy over a uniform depositional surface: spatial variability and measurement tools. *Cold Regions Science and Technology*, *37*(3), 289-298.

Hétu, B. (2007). Les conditions météorologiques propices au déclenchement des avalanches de neige dans les corridors routiers du nord de la Gaspésie, Québec, Canada. *Géographie physique et Quaternaire*, *61*(2-3), 165–180.

Hétu, B., & Bergeron, A. (2004). *Les avalanches au Québec: analyse des conditions météorologiques et des facteurs de terrain propices au déclenchement des avalanches*. Rapport préparé dans le cadre du Programme conjoint en sécurité-avalanche au Québec.

Hétu, B., & Vandelac, P. (1989). La dynamique des éboulis schisteux au cours de l'hiver, Gaspésie septentrionale, Québec. *Géographie physique et Quaternaire*, *43*(3), 389-406.

Ikeda, S., Wakabayashi, R., Izumi, K., & Kawashima, K. (2009). Study of snow climate in the Japanese Alps: Comparison to snow climate in North America. *Cold Regions Science and Technology*, *59*(2-3), 119-125.

Jamieson, B. (2006). Formation of refrozen snowpack layers and their role in slab avalanche release. *Reviews of Geophysics*, *44*(2).

Joosen, C. (2008). *The importance of micro-scale avalanche forecasting in Mount Washington's Tuckerman and Huntington Ravines*. Communication présentée au International Snow Science Workshop, Whistler, British-Columbia.

Karmosky, C. (2007). *Synoptic climatology of snowfall in the northeastern United States: an analysis of snowfall amounts from diverse synoptic weather types*. University of Delaware.

Kronholm, K., Schneebeli, M., & Schweizer, J. (2004). Spatial variability of micropenetration resistance in snow layers on a small slope. *Annals of Glaciology*, *38*, 202-208.

Kronholm, K., & Schweizer, J. (2003). Snow stability variation on small slopes. *Cold Regions Science and Technology*, *37*(3), 453-465.

LaChapelle, E. R. (1965). *Avalanche forecasting-a modern synthesis*. US Department of Agriculture.

Landry, C., Birkeland, K., Hansen, K., Borkowski, J., Brown, R., & Aspinall, R. (2004). Variations in snow strength and stability on uniform slopes. *Cold Regions Science and Technology*, *39*(2-3), 205-218.

Lehning, M., Bartelt, P., Brown, B., Russi, T., Stöckli, U., & Zimmerli, M. (1999). SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations. *Cold Regions Science and Technology*, *30*(1-3), 145-157.

Li, L., & Pomeroy, J. W. (1997). Estimates of threshold wind speeds for snow transport using meteorological data. *Journal of Applied Meteorology*, *36*(3), 205-213.

Lutz, E., & Birkeland, K. W. (2011). Spatial patterns of surface hoar properties and incoming radiation on an inclined forest opening. *Journal of Glaciology*, *57*(202), 355-366.

Lutz, E., Birkeland, K. W., Kronholm, K., Hansen, K., & Aspinall, R. (2007). Surface hoar characteristics derived from a snow micropenetrometer using moving window statistical operations. *Cold Regions Science and Technology*, *47*(1-2), 118-133.

Madore, J.-B., Langlois, A., & Côté, K. (2018). Evaluation of the SNOWPACK model's metamorphism and microstructure in Canada: a case study. *Physical Geography*, 1-22.

McClung, D., & Schaerer, P. (2006). *The Avalanche Handbook, 3rd Edition*. Leicester, England: The Mountaineers Books.

Mock, C. J., & Birkeland, K. W. (2000). Snow avalanche climatology of the western United States mountain ranges. *Bulletin of the American Meteorological Society*, *81*(10), 2367-2392.

Mock, C. J., Carter, K. C., & Birkeland, K. W. (2017). Some Perspectives on Avalanche Climatology. *Annals of the American Association of Geographers*, *107*(2), 299-308.

Mott, R., Schirmer, M., Bavay, M., Grünewald, T., & Lehning, M. (2010). Understanding snow-transport processes shaping the mountain snow-cover. *The Cryosphere*, *4*(4), 545-559.

NOAA. (2018). Daily weather maps, National weather Service: Weather Prediction Center. Consulted at https://www.wpc.ncep.noaa.gov/dailywxmap/index.html.

Oke, T. R. (2002). *Boundary layer climates* (2nd). London: Routledge.

Perry, L. B., Konrad, C. E., Hotz, D. G., & Lee, L. G. (2010). Synoptic classification of snowfall events in the Great Smoky Mountains, USA. *Physical Geography*, *31*(2), 156-171.

Pyrcz, M., & Deutsch, C. (2003). The whole story on the hole effect. *Geostatistical Association of Australasia, Newsletter*, *18*, 3-5.

Reuter, B., Richter, B., & Schweizer, J. (2016). Snow instability patterns at the scale of a small basin. *Journal of Geophysical Research: Earth Surface*, *121*(2), 257-282.

Reuter, B., & Schweizer, J. (2018). Describing snow instability by failure initiation, crack propagation and slab tensile support. *Geophysical Research Letters*.

Reuter, B., Schweizer, J., & van Herwijnen, A. (2015). A process-based approach to estimate point snow instability. *The Cryosphere*, *9*(3), 837-847.

Reuter, B., van Herwijnen, A., Veitinger, J., & Schweizer, J. (2015). Relating simple drivers to snow instability. *Cold Regions Science and Technology*, *120*, 168-178.

Rotunno, R., Curry, J., Fairall, C., Friehe, C., Lyons, W., Overland, J., ... Geernaert, G. (1992). Coastal Meteorology, A review of the state of the science. *Panel on Coastal Meteorology, Committee on Meteorological Analysis, Prediction, Research, Board on Atmospheric Sciences Climate, Commission on Geosciences, Environment, Resources*.

RStudio. (2016). *RStudio: integrated development for R. RStudio, Inc., Boston. URL*.

Schweizer, J., Bruce Jamieson, J., & Schneebeli, M. (2003). Snow avalanche formation. *Reviews of Geophysics*, *41*(4).

Schweizer, J., Jamieson, J. B., & Skjonsberg, D. (1998, 12-16 May). *Avalanche forecasting for transportation corridor and backcountry in Glacier National Park (BC, Canada)*. Communication présentée au 25 Years of Snow Avalanche Research,, Voss, Norway.

Schweizer, J., & Kronholm, K. (2007). Snow cover spatial variability at multiple scales: Characteristics of a layer of buried surface hoar. *Cold Regions Science and Technology*, *47*(3), 207-223.

Schweizer, J., Kronholm, K., Jamieson, J. B., & Birkeland, K. W. (2008). Review of spatial variability of snowpack properties and its importance for avalanche formation. *Cold Regions Science and Technology*, *51*(2-3), 253-272.

Schweizer, J., & Reuter, B. (2015). A new index combining weak layer and slab properties for snow instability prediction. *Natural Hazards Earth System Sciences*, *15*(1), 109-118.

Shandro, B., & Haegeli, P. (2018). Characterizing the nature and variability of avalanche hazard in western Canada. *Natural Hazards Earth System Sciences*, *18*(4), 1141-1158.

Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israelson, C., Tremper, B., ... Kelly, J. (2018). A conceptual model of avalanche hazard. *Natural Hazards*, *90*(2), 663-691.

Sturm, M., & Benson, C. (2004). Scales of spatial heterogeneity for perennial and seasonal snow layers. *Annals of Glaciology*, *38*, 253-260.

Sturm, M., Holmgren, J., & Liston, G. E. (1995). A seasonal snow cover classification system for local to global applications. *Journal of Climate*, *8*(5), 1261-1283.

Trujillo, E., Ramírez, J. A., & Elder, K. J. (2007). Topographic, meteorologic, and canopy controls on the scaling characteristics of the spatial distribution of snow depth fields. *Water Resources Research*, *43*(7).

Trujillo, E., Ramírez, J. A., & Elder, K. J. (2009). Scaling properties and spatial organization of snow depth fields in sub-alpine forest and alpine tundra. *Hydrological Processes: An International Journal*, *23*(11), 1575-1590.

Vantrepotte, V., & Mélin, F. (2010). Temporal variability in SeaWiFS derived apparent optical properties in European seas. *Continental Shelf Research*, *30*(3-4), 319-334.

Winstral, A., Elder, K., & Davis, R. E. (2002). Spatial snow modeling of wind-redistributed snow using terrain-based parameters. *Journal of hydrometeorology*, *3*(5), 524-538.