The Rainy Continental Snow climate: Global comparison with 40 years of snow cover modeled in the Chic-Chocs, northeastern Appalachians mountains.

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ABSTRACT. This study provides a comprehensive analysis of the snow and avalanche climate of the Chic-Chocs region of the Gaspé Peninsula, located in the northeastern Appalachians of eastern Canada. The data revealed two major components of the snow climate: a cold snow cover combined with a maritime influence causing melt/ice layers through rain-on-snow events. The CRCM6-SNOWPACK model chain was good at representing the seasonal mean of climatic indicators, snow grain size and a snow problem type that well represented the snow climate of the study region. The global comparison shows that the snow climate is different from other areas in western North America, but similar to Mt. Washington (New Hampshire, USA) and central Japan. We show a clustering based solely on avalanche problem types, which showed that the onset date of wet snow problems divided most of the winter into three clusters. We compare these clusters with the French Alps and show

some similarities, moving away from a traditional snow climate description. The paper concludes that the use of advanced snow cover modeling combined with the Reuter and others (2022) method represents a new potential framework to improve our understanding and classification of snow climates, ultimately contributing to improved forecasting and risk management in similar regions.

INTRODUCTION

Snow climate classifications were initially developed to characterize the climate of mountainous regions, often to understand the conditions driving avalanche hazard (Armstrong and Armstrong, 1987; LaChapelle, 1965; McClung and Schaerer, 2006; Roch, 1949). In hydrology and climate modeling, the term "snow climate" has been employed to delineate seasonal average snow cover properties, including total depth, presence of depth hoar, ice layers, and snow temperature (Sturm and others, 1995). Within the field of snow avalanche studies, the term "snow climate" specifically denotes the properties of the snow cover that are relevant for the formation of snow avalanches (Hägeli and McClung, 2003). Understanding the snow climate classification of a given mountain region is essential for developing location-specific avalanche mitigation and forecasting programs (e.g. McClung and Schaerer, 2006).

The snow climate classification has three primary patterns: Maritime, Continental, and Transitional (LaChapelle, 1965). The Maritime snow climate is characterised by warm temperatures and heavy snowfall, with major instabilities predominantly attributed to recent snow loading in the upper snow cover (Haegeli and McClung, 2007; Mock and Birkeland, 2000). Avalanche forecasting programs in these regions heavily rely on weather observations (McClung and Schaerer, 2006). Conversely, the Continental snow climate is distinguished by cold temperatures and light snowfall, featuring weak persistent layers in the snow cover that necessitate systematic monitoring for forecasting snow avalanches (McClung and Schaerer, 2006). The Transitional snow climate exhibits characteristics of both Maritime and Continental snow climates (Haegeli and McClung, 2007). However, the description of a transitional snow climate is often generalized and has been primarily delineated in western North America, Haegeli and McClung (2007) suggest that other regions experiencing varying degrees of continental and maritime influences should be included to enrich the understanding of this transitional snow climate.

Mock and Birkeland (2000) introduced a flowchart aimed at classifying snow climates, outlining snow cover processes pertinent to avalanche hazard assessment. Their approach utilized meteorological data to categorize individual winter seasons into distinct snow climates. However using only meteorological data is insuficient to describe snow instability, as Schweizer and others (2003) demonstrated that the physical properties of slabs and weak layers serve as critical indicators of avalanche formation (Hägeli and McClung, 2003). Recognizing this, Haegeli and McClung (2007) emphasized the necessity of incorporating additional snow stratigraphy information to refine the description of snow climates. They proposed expanding the Mock and Birkeland (2000) flowchart to integrate avalanche and snow observations, particularly focusing on persistent weak layer observations, thus introducing the term "snow and avalanche climate" (Haegeli and McClung, 2007). This inclusion provides valuable insights into the percentage of avalanche activity on persistent weak layers and the specific types of persistent weak layers characterizing each snow and avalanche climate zone. This refinement is especially pertinent in delineating Transitional snow climates, where the interplay of Continental and Maritime influences leads to distinctive persistent weaknesses in particular regions.

The concept of "avalanche problem types" refers specific weather events and snow cover properties characterizing different types of avalanche problems, such as wind slab or persistent slab avalanche problems Statham and others (2018); EAWS (2019). These avalanche problem types represent the primary concern for avalanche forecasters regarding specific meteorological and snow cover conditions. They are the foundation for various avalanche operational hazard forecasting to communicate the avalanche hazards in North America (Statham and others, 2018), and Europe (Techel and others, 2020).

Building upon this framework, Shandro and Haegeli (2018) integrated avalanche problem data type with the Mock and Birkeland (2000) flowchart to enhance the characterization of snow avalanche hazard in western Canada. While the methodology of Mock and Birkeland (2000) offers a generalized description of snow climate across multiple winter seasons, the incorporation of avalanche problem type data facilitates a more nuanced understanding, addressing daily concerns for forecasters throughout the season. However, building a temporally extensive database of forecast avalanche problem types can be difficult without avalanche forecasting data. To fill this gap and to provide an independent methodology, Reuter and others (2022) proposed a method to derive avalanche problem types from snow cover model output such as SNOWPACK (Lehning and others, 1999) or SURFEX/CROCUS (Vionnet and others, 2012). This method allows to characterise based on weather forecasting reanalysis data and snow cover modeling, for instance, and hence, omitting the use of forecasting data.

Various combinations of the methodologies outlined above have been employed to describe and classify additional regions, utilizing different data types primarily based on data availability. For instance, Ikeda and others (2009) utilized the Mock and Birkeland (2000) flowchart alongside snow cover data to delineate the snow climate of the Japanese Alps. Their findings for the Japanese Coastal mountains exhibited similarities with the Maritime climate zone. However, the Central Japanese Alps, characterised by a thin snow cover, cold temperatures conducive to persistent weakness development, and a significant amount of rainfall, did not align with any of the three main snow climates. Consequently, they introduced the term "Rainy Continental" for the Central Japanese Alps (Ikeda and others, 2009). Similarly, Eckerstorfer and Christiansen (2011) utilized snow profile data to describe the snow climate of Svalbard's main settlement, Longyearbyen. Their analysis highlighted a thin snow cover, persistent weaknesses, and substantial ice layers attributed to maritime influences, which led them to propose the term "High Arctic Maritime" for Central Svalbard (Eckerstorfer and Christiansen, 2011). Recently, Reuter and others (2023) characterized the snow climate of the French alps using two approaches, the snow climate classification algorithm of Mock and Birkeland (2000) and using avalanche problem types based on snow cover simulations. With their approach, they put forward the idea of classifying snow and avalanche climates based on avalanche problem type occurrences. Their comparisons with the standard snow climate classification suggests that in the French alps avalanche problem occurrences provide for a more detailed characterisation.

In eastern Canada, The Chic-chocs mountains in the Gaspé Peninsula are prone to snow avalanches. Multiple studies have highlighted the influence of snowstorms and thaw events on the local snow avalanche dynamic (Fortin and others, 2011; Gauthier and others, 2017; Germain and others, 2009; Hétu, 2010). Despite the Köppen classification indicating a humid continental climate, the region experiences a significant maritime influence, complicating the classification of the snow and avalanche climate (Fortin and others, 2011; Gagnon, 1970; Gauthier and others, 2017). While the winter climate of the region has been extensively documented (Fortin and others, 2011; Fortin and Hétu, 2014; Gagnon, 1970; Gauthier and others, 2017), the description primarily relies on seasonal average climate conditions not directly relevant to avalanche formation. Hence, comprehensive analysis integrating snow cover and weather data relevant to avalanche formation holds promise to elucidate the region's snow and avalanche climate.

Given the presence of established approaches in snow climatology and the importance to better understand the snow and avalanche climate of the Chic-Chocs mountains, we aim at the following objectives:

1) Describe the snow and avalanche climate for the Chic-Chocs mountains, 2) Compare the dataset Chic-Chocs region with other mountain ranges such as Mount Washington (New Hampshire, USA), Central Japan and the French Alps. We conclude the paper by discussing how the current snow climate observed in the Chic-Chocs could evolve regarding climate change.

Study area

This study focuses on the Chic-Chocs mountains, a northern extension of the Appalachian Mountains, which forms an inland massif serving as the backbone of the Gaspé peninsula (Figure 1). This central massif comprises sub-alpine and alpine terrain, ranging in elevation from 800 to 1200 meters above sea level (m a.s.l.), and is encompassed by a lower plateau situated at 400-500 m a.s.l. (Figure 1). The study area is mainly the Avalanche Québec forecasting area. This non-profit organization has been issuing avalanche bulletins for backcountry users in the Chic-Chocs since 2000. Since Avalanche Québec is now part of the Avalanche Canada forecasting program, the organisation will benefit from a snow and avalanche climate to inform hazard forecasting as weell as risk management in the region, while such procedures were established in the climate regions of Western Canada.

The Chic-Chocs region receives approximately 800 mm of precipitation annually, while the high plateau of the interior receives around 1,600 mm (Fortin and others, 2011; Gagnon, 1970; Germain and others, 2010). Snowfall typically occurs from December to April, accompanied by an average of about 60 mm of rainfall per winter (Fortin and others, 2011). The mean annual temperature, spanning from 1971 to 2010, varies from 3°C along the Gaspé North Coast to -4°C at 1268 m (Mt Jacques-Cartier) (Gray and others, 2017). The regional climate exhibits contrasting weather patterns: 1) cold Arctic air masses often bring northwesterly winds with temperatures dropping below -20 °C, and 2) continental low-pressure systems, usually accompanied by northeasterly winds, resulting in temperatures near the freezing point and potential rain. These weather systems, commonly referred to as the Alberta Clipper, the Colorado Low, and the Hatteras Low, significantly influence the Gaspé Peninsula's weather, impacting the type of precipitation experienced in the area (Fortin and Hétu, 2014). The interaction of these weather patterns with the peninsula's topographic features creates a snow accumulation pattern conducive to avalanche formation (Germain and others, 2010). Most avalanches in the region are natural releases occurring during storms (Fortin and others, 2011; Gauthier and others, 2017; Germain and others, 2009; Hétu, 2010).

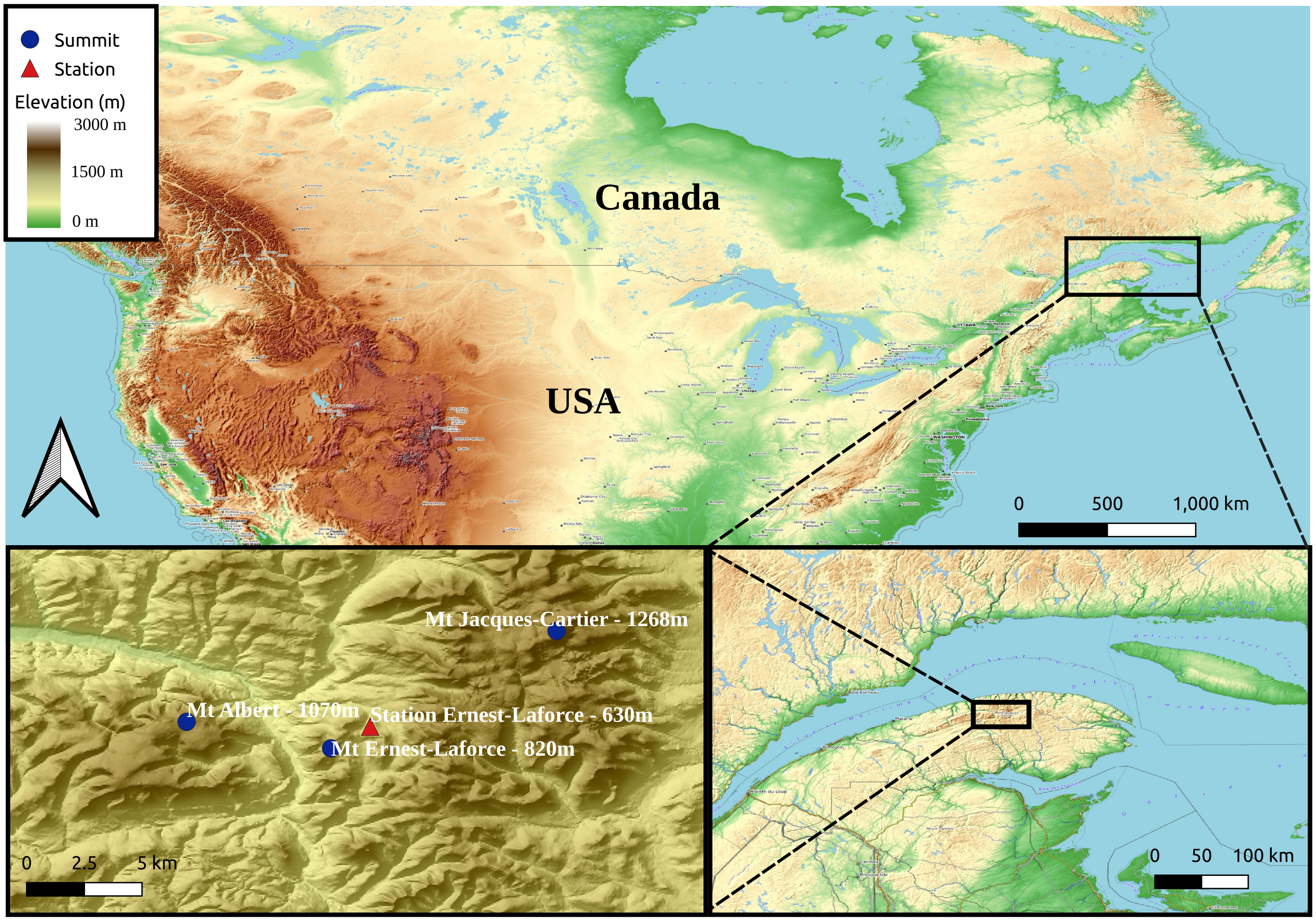

Fig. 1. Localisation map of the study inside North America. The input represents different spatial scale of the study area with the different summits around the weather station Ernest-Laforce 630 m.

METHODS

Classification strategy

To provide a comprehensive description of the snow and avalanche climate, we used several methodologies drawn from work on snow and avalanche climatology widely used over the past decades (Mock and Birkeland, 2000; Shandro and Haegeli, 2018; Sturm and others, 1995; Reuter and others, 2022). While these methodologies formed the basis of our approach, we adapted them by selectively incorporating relevant aspects tailored to our specific research needs. This approach integrated several types of data relevant to understanding avalanche formation.

We used the Mock and Birkeland (2000) flowchart, which uses meteorological data to outline the general snow climate. We then retrieved from snow cover simulations the distribution of snow grain types for the whole snow cover described by Sturm and others (1995), but also for the critical weak layers. These snow cover data not only clarify the dominant metamorphic processes, but also help to identify which snow grain types characterised the weak layers of the study area. In addition, we have included avalanche problem types to characterize avalanche hazard, inspired by the approach of Shandro and Haegeli (2018). The avalanche problem types were derived from simulations with the SNOWPACK model (Lehning and others, 1999), following the framework described in Reuter and others (2022). They characterize snow instability patterns for every day. This type of data serves complements the description of the snow climate.

Finally, similarly to Reuter and others (2023), a temporal cluster analysis has been performed over the 40-year period, based on the avalanche problem type. This analysis should show the different types of winters that the region can experience, while providing a different point of view from the classic snow climate classification of Mock and Birkeland (2000). It is important to note that the database includes data representing the winter avalanche regime from December 1 through March 31. Data representing the spring avalanche regime were not included in this analysis.

Meteorological data

Meteorological data were collected at a weather station located in the Chic-Chocs range. The weather station, named Ernest-Laforce weather station (CAELA), is located on the north slope of Mt Ernest-Laforce at 630 m a.s.l. (Figure 4). The data set covers the winter seasons from December 1 to March 31 for the winter seasons 2012-13 to 2021-22. Hourly data for mean air temperature, snow depth, and precipitation (measured by a weighing precipitation gauge) were used to calculate the meteorological variables required for the Mock and Birkeland (2000) flow chart: daily mean air temperature (°C), total snowfall (cm), total precipitation (mm), total snow water equivalent (SWE in mm), and mean December temperature gradient (°C/m). Rainfall and SWE were derived from total precipitation using a rain/snow threshold of 1.2 °C with the hourly mean air temperature. To minimize the misclassification of precipitation events - which could lead to erroneous snow- climate classification - snow events were confirmed by a significant increase ($>$ 2 cm) in snow height within the next two hours following the precipitation event. Rain events were similarly validated by stable or decreasing snow height (0 cm or 1 cm). Snow depth was measured hourly using an ultrasonic snow depth sensor (SR50 from Campbell Scientific) on an automated weather station. Snowfall was processed as the difference between each hour and then summed for the entire season. The mean temperature gradient in December was determined using the mean air temperature and snow depth for December, assuming zero degree Celsius at the snow-soil interface Mock and Birkeland (2000). The observed meteorological indicators used in the Mock and Birkeland (2000) algorithm are used as a basis for comparing the same meteorological indicators derived from the climate simulation presented below.

Climate simulation data

We choose to use climate simulation data to extend the temporal scope of our study from 1982 to 2022. These climate models represent different components of the climate system, such as the atmosphere, ocean, land surface, ice, and ecosystems, and are integrated to project the climate of a particular region or domain. In this research, we use the sixth generation of the Canadian regional climate model (CRCM6/GEM5.0), which is currently under development at the Centre pour l'Étude et le Simulation du Climat à l'Échelle Régional (ESCER) of the University of Quebec at Montréal (UQAM). Two studies have recently evaluated the performance of this newly developed model in North America (Moreno-Ibáñez and others, 2023; Roberge and others, 2024). The version of CRCM6/GEM5.0 used in this study is based on version 5.0.2 of the Global Environmental Multiscale Model (GEM5) (McTaggart-Cowan and others, 2019; Girard and others, 2014), which serves as the operational numerical weather prediction model for the Meteorological Service of Canada. The CRCM6 model uses a 12 km (0.11 °) spatial grid based on the Regional Deterministic Prediction System (RDPS) configuration of the 5.0.2 version of the Global Environmental Multiscale model (GEM5) (McTaggart-Cowan and others, 2019; Girard and others, 2014). This model was chosen for its spatial downscaling capabilities and hourly time step, which we selected from 1982 to 2022.

To increase the overall representativeness of the modeled data, four grid points were selected around the coordinates of the CAELA weather station and the mean value was extracted. The data were provided and processed by the ESCER. The mean elevation of the four grid points is 679 m, which represents a slight overestimation of the actual weather station, which is at 630 m. Previously, Imbach and others (2024) observed an underestimation of snowfall and snow height in the CRCM6 dataset for the CAELA weather station study site. The underestimation was rate dependent, and the underestimation was greater at higher snow rate precipitation. Their precipitation bias assessment analysis and correction was used to positively correct the observed underestimation. The correction made was based on the correction made at Rogers Pass, Western Canada by (Bellaire and others, 2011). Furthermore, a statistical validation of the CRCM6 against *in-situ* recorded data showed an overall strong representativeness. Their correction was applied to the snow precipitation and snow depth of the CRCM6 outputs.

Meteorological data from other locations

To compare our data with potentially similar locations around the globe and existing snow climate classification, we adapted the boxplot figure from Mock and Birkeland (2000), incorporating each of the climate indicators to visually compare the mentioned regions. We also used data directly from the snow study of Ikeda and others (2009) for the Central Japanese Alps, and data from Mt. Washington in New Hampshire, USA (Meloche, 2019), which is also similar to the Chic-Chocs.

Snow cover modeling

The snow cover model SNOWPACK is a multilayer one-dimensional thermodynamic model and was used to simulate the snow cover stratigraphy and properties for each snow season (Lehning and others, 1999). The required meteorological data input were driven from the CRCM6 model, which were air temperature, relative humidity, wind speed and direction, short and long wave radiation (incoming and outgoing), total precipitation, and snow height. In this study, SNOWPACK was run using hourly CRMC6 data with snow height forcing. The model parameters were based on previous work and validation performed by members of the research team for the same study area (Côté and others, 2017) and also in western Canada (Madore and others, 2018, 2022). We chose to use the default SNOWPACK snow/rain threshold of 1.2 °C, and the main parameterizations (SNOWPACK parameters) used were the BELLAIRE snow density parameterization, the MONTI hardness parameterization, the Bucket water percolation model, and the

MO-MICHLMAYR atmospheric stability . The snow height in the simulation was enforced with the snow height predicted by the CRCM6 model, with the corrected precipitation of Imbach and others (2024). The snow cover was simulated every hour from October 1 to May 31, on the flat and also on two 38° virtual slopes on a northern and southern aspect.

Snow grain type

The seasonal snow grain type distribution was computed from the snow cover model output by adding the thickness of each layer to a snow grain type class such as precipitation particles (PP), melt forms (MF), or faceted crystals (FC). This process is repeated daily from December 1 to March 31. The frequency distribution is normalized by the sum of all layer thicknesses for both north and south virtual slope during the winter from December to March.

In order to assess the validity of the snow grain type obtained from the snow cover model, we compared it from the snow grain type frequency retrieved from snow profile observations made by the Avalanche Québec, which is responsible for avalanche forecasting in the Chic-Chocs region, for the winter of 2015 to 2018 (Meloche, 2019). The snow profiles were made at different aspects and elevations throughout the region, with approximately 25 snow profiles per winter.

Avalanche problem type

Weak layer identification

The avalanche problem type was derived from the output of the SNOWPACK model i.e., from both, north and south-facing slope simulations, following the methodology proposed by Reuter and others (2022). The following section describes the general procedure of the method, for more details please refer to the original paper. This method evaluates potential persistent and non-persistent instabilities on each day, which could be either prone to natural release or artificial triggering. For the purpose of this study, only natural release was considered. The non-persistent weak layer is composed of either precipitation particles (PP), decomposed and fragmented particles (DF), and faceted rounded grains (FCxr). The persistent weak layers are composed of faceted crystals (FC - FCxr), surface hoar crystals (SH) and depth hoar crystals (DH).

If a potential weak layer was present the day before or potentially buried, the properties of the slab overlaying this potential weak layer is judged. A minimum slab thickness of 0.18 m and a slab density of at least 100 kg m^-3 are required for a critical slab-weak layer combination (Reuter and others, 2022). Four indices were then used to classify all potential slab-weak layer combinations in view of natural release. The S_N (natural) index was computed for each layer within the snowpack, defined by a ratio of the gravitational shear stress τ_g induced by the weight of the overlying slab and the shear strength of the weak layer:

$$S_N = \frac{\tau_g}{\tau_p}, \tag{1}$$

where $\tau_g = \rho g h \sin\psi$ is defined by the slab density ρ, the gravitational acceleration g, the slab height h, and the slope angle ψ. The time to failure t_f was also used to determine the natural stability of the layers, developed by Conway and Wilbour (1999). The time to failure is the time derivative of S_N:

$$t_f = \frac{S_N(t) - 1}{\frac{dS_N}{dt}}. \tag{2}$$

A second stability indicator is the critical crack propagation length a_c, which is the length required for crack propagation to begin. (Richter and others, 2019) proposed a method to derive the critical crack length from the SNOWPACK simulation based on stress and strength approach (Gaume and others, 2017) instead of using the weak layer fracture energy (Heierli and others, 2008). The method was also adapted with an empirically fitted F_{wl} parameter to improve the predictive performance with the SNOWPACK model. The critical crack length was calculated using the following expression, which was coded in the SNOWPACK module from Gaume and others (2017):

$$a_c = \Lambda \left[\frac{-\tau + \sqrt{\tau + 2\sigma(\tau_p - \tau)}}{\sigma} \right], \tag{3}$$

where $\sigma = \rho g D cos\psi$ and λ is a characteristic length of the system defined by:

$$\Lambda = \sqrt{E^{'} D F_{wl}}, \tag{4}$$

where $E^{'} = E/(1 - v^2)$, v is the Poisson ratio set to 0.3, F_{wl} is the fitted parameter developed by Richter and others (2019). All two stability indices S_N and a_c mentioned above are already available as output variables in the SNOWPACK code (v3.6). The time to failure t_f was coded in Python based on the time derivative of S_N.

Based on these three indices, we classified each potential layer as an unstable weak layer using the thresholds determined by Reuter and others (2022). A weak layer was classified as critical for natural release if $S_N < 3.6$ and $t_f < 18$ h, and $a_c < 0.32$ m. Then, for each unstable weak layer, we classified it as a persistent or non-persistent weak layer depending on the weak layer grain type. The snow grain types of each critical weak layer were counted to get a frequency of weak layer snow grain type of the simulated 40-year period.

Assigning Avalanche problem

The following avalanche problem types were derived from the SNOWPACK model output: new snow (NAP), wind slab (WSAP), persistent (PAP), and wet (WAP), based on the methodology developed by Reuter and others (2022). On each day, after classifying the critical persistent and non-persistent weak layers, we look at the concurrent snow load modeled in SNOWPACK. A non-persistent weak layer within a 24-hour snowfall (HN24) greater than 5 cm is classified as a new snow problem (NAP). If a persistent critical weak layer is loaded by a precipitation rate greater than 0.05 m/24h, the algorithm will classify it as a persistent avalanche problem (PAP) and a new snow avalanche problem (NAP). The same procedure is used for a wind slab avalanche problem (WSAP) with a 24h wind transport (wind_trans24) greater than 0.4 m/24h and a non-persistent weak layer. A WSAP is also possible if the wind_trans24 is above the threshold and soft snow is present on the surface within three days. The algorithm will classify both a PAP and WSAP when the wind transport threshold is reached with an unstable persistent weak layer.

The assessment of the wet-snow avalanche problem is based on the liquid water content index developed by Mitterer and Schweizer (2013) along with the number of days since isothermal conditions were reached (Baggi and Schweizer, 2009). This index measures the liquid water per snow volume for each SNOWPACK layer, with an averaging process that considers the thickness of these layers to determine the total liquid water content of the snow cover. The index compares the total water content of the snow cover to a critical threshold of 1% water by ice volume (Mitterer and others, 2016). A liquid water content index of 1 indicates the onset of natural wet-snow avalanches, then, the snow cover returns to a stable state after four days of sustained isothermal conditions (Baggi and Schweizer, 2009). We assign the avalanche problem for both the virtual north and south face slope of every winter of the 40-year period. We used the find_aps.py function to find all avalanche problem types from the SNOWPACK outputs based on the methodology of Reuter and others (2022), in AVAPRO available in the package the *snowpacktools* from the public repository of the Avalanche Warning Service Operational Meteo Environment AWSOME (AWSOME Core Team, 2024).

In order to assess the validity of the avalanche problem type derived from the SNOWPACK modeling, we compared it with the forecasted avalanche problem type from Avalanche Québec for the winter of 2012 to 2018 (Meloche, 2019). The predicted avalanche problem types are the forecaster's assessment for the upcoming forecast period based on meteorological observations, snow cover observations, and weather forecasts. The forecast period was two days for winters 2013 to 2015 and daily for winters 2016 to 2018.

Clustering

Finally, we performed a k-means cluster analysis to explore a different classification of the avalanche characteristics of the study area. The k-means is a clustering analysis that uses the proximity to a geometric position in the feature coordinate space (Macqueen, 1967). The k-means was run with data from 40 winters, including north- and south-facing slope simluations for the avalanche problem type. We neglected the climate indicators and the snow grain type to reduce dimensionality and to replicate the same method as Reuter and others (2023). In addition, the avalanche problem type integrates the weather context and snow grain type from the critical weak layer. To select the ideal number of clusters, we computed the silhouette score and the Calinski-Harabasz score for clusters ranging from 2 to 10. We selected the number of clusters with the maximum values of Silhouette score per number of cluster, and Calinski-Harabasz score. The number of clusters when one of the individual clusters were below the average score was not considered. We also performed principal component analysis on the dataset to explore linearity between variables and to ease visualization of our clustering results. The result of the clustering analysis will be compared to the French alps were a similar analysis is available for comparison Reuter and others (2023).

RESULTS

Snow Climate classification

10 years of meteorological data

As a first result, we present 10 years (2013-2022) of meteorological data recorded at the Mt Ernest-Laforce weather station and data simulated by the climate model CRCM6. The Chic-Chocs study areas generally exhibited cold average winter temperatures (meanTA $<$ -7°C) and limited total winter snow precipitation (Snow $<$ 450 mm SWE). The winters of 2016 and 2021 showed warmer conditions, but only the winter of 2021 showed significant rain during the winter season (Table 1). The winters of 2013 and 2020 were also warmer, but less than 2016 and 2021, with a significant amount of Rain (67.8 and 77.0 mm, respectively).

Table 1. Results of the Mock and Birkeland (2000) classification with weather station Mt Ernest-Laforce and the CRCM6 climate model. The year in the column winter represent the month of January, indicating that the winter of the present year includes December of the prior year.

	Rain (mm)		meanTA (°C)		meanDEC (°C m^{-1})		SWE (mm)		Snow (cm)	
Winter	CAELA	CRCM6	CAELA	CRCM6	CAELA	CRCM6	CAELA	CRCM6	CAELA	CRCM6
2013	67.8	117.6	-10.0	-10.5	16.2	19.1	489.4	470.1	713.8	328.8
2014	6.0	15.5	-13.8	-15.3	13.7	35.0	474.4	465.8	689.3	318.8
2015	48.0	34.1	-14.7	-14.5	13.7	11.8	426.4	425.5	446.7	277.8
2016	42.3	37.6	-9.5	-10.7	NA	29.1	422.3	453.4	NA	314.9
2017	15.7	36.8	-11.0	-12.4	21.7	27.5	475.9	516.6	725.1	374.3
2018	50.7	37.4	-10.7	-12.4	17.9	19.7	405.6	491.9	516.6	368.2
2019	15.5	52.0	-12.6	-14.0	19.1	17.7	211.4	512.8	493.6	341.6
2020	77.0	54.6	-10.7	-12.1	13.1	18.4	444.3	441.2	437.0	303.7
2021	93.6	106.1	-8.6	-9.7	16.1	22.3	502.3	425.3	546.4	339.3
2022	15.7	43.7	-12.2	-13.3	10.9	16.5	509.4	570.0	535.4	419.4

The meanTA fell below -7°C, and the meanDEC was consistently above 10°C m^{-1}. This combination of cold mean air temperatures and sparse snow cover likely contributed to the pronounced temperature gradients observed (Table 1).

Figure 2 shows the difference between the CAELA weather station and the CRCM6 model. The SWE estimation with the CRCM6 model are good with the exception of the winter of 2019. We suspected a problem with the precipitation gauge during this winter, so the error may not be from the CRCM6 model. However, despite the precipitation correction and snow height forcing in SNOWPACK, the snow height (Hs) and snowfall were underestimated by the CRCM6 model. Figure 2 shows that the CRCM6 model simulated colder temperatures compared to the weather observations. However, this colder bias did not translate into a systematic underestimation of precipitation, which has no clear systematic bias with some winters precipitation being underestimated and others overestimated. Finally, the mean December temperature gradient was slightly overestimated by CRCM6 with less snow height.

The results of the snow climate classification derived from Mock and Birkeland (2000) flowchart indicated a predominantly continental climate for 8 winters over 10, and maritime classification for the remaining two winters (Table 1). The winter 2013 had a continental classification at the weather station, but a maritime classification with the CRCM6 model. The key determinant in classifying most winter sea-

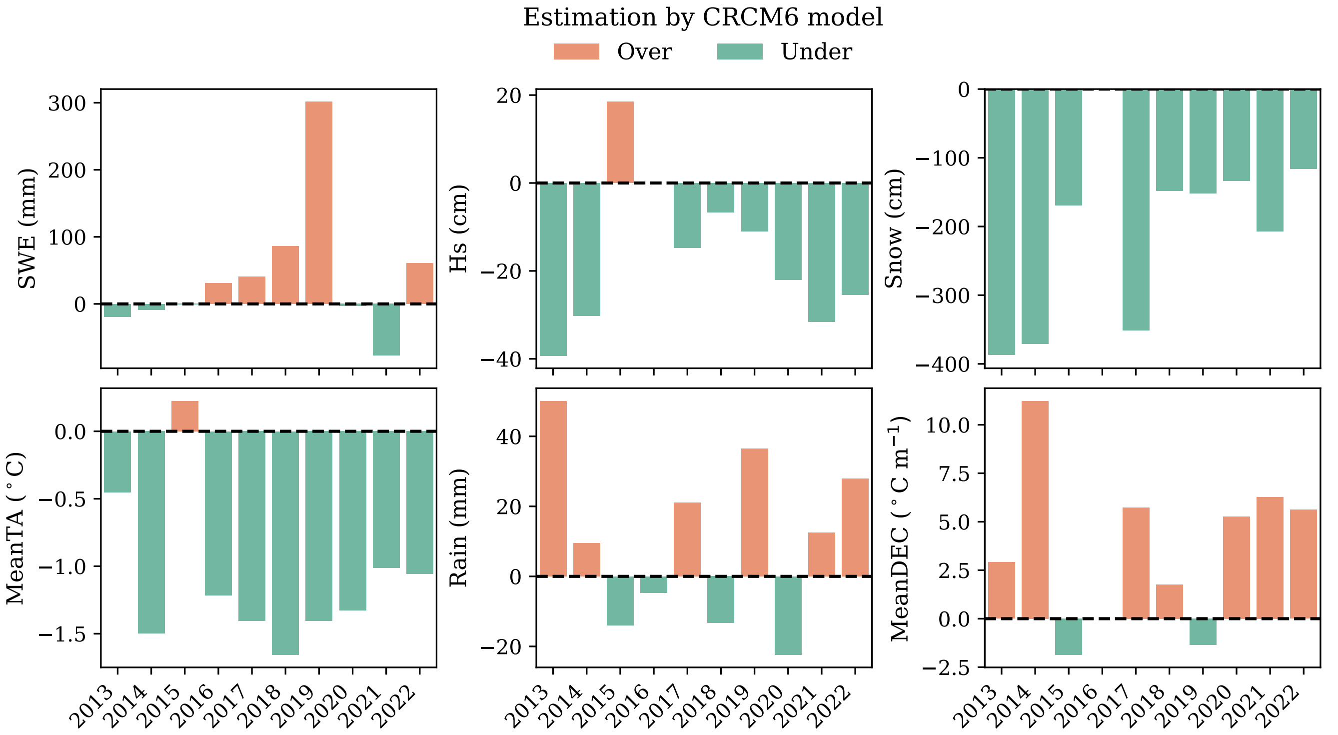

Fig. 2. Estimation of the climatic indicators used in Mock and Birkeland (2000) algorithm by the CRCM6 model, except for the snow height Hs. The estimation is compared to the weather observations at the CAELA station. The positive difference represents an overestimation (orange) of the CRCM6 model, and the negative difference represents an underestimation (blue) of the CRCM6 model.

sons was the mean December temperature gradient (meanDEC), which exceeded 10°C/m for a continental climate and rain amounts exceeding 80 mm for a maritime climate (Table 1). The algorithm never met the "snow accumulation" criterion for classification into maritime and transitional snow climates during the classification process for both weather data (weather station and CRCM6).

40 years snow climate classification

Figure 3 shows a time series of the rain and mean air temperature for the last 40-winter simulations from the CRCM6 model. The classification results is also shown by the background color for each year where blue is for continental and red for maritime, as the transitional snow climate was never classified for the 40 winters. The rain indicator was the only indicator that classified some winter as maritime (above the dashed line in Figure 3). Most of the winters (33/40) were classified as continental based on the mean December temperature (meanDEC). The mean air temperature is relatively cold and never exceeds -8°C, which is

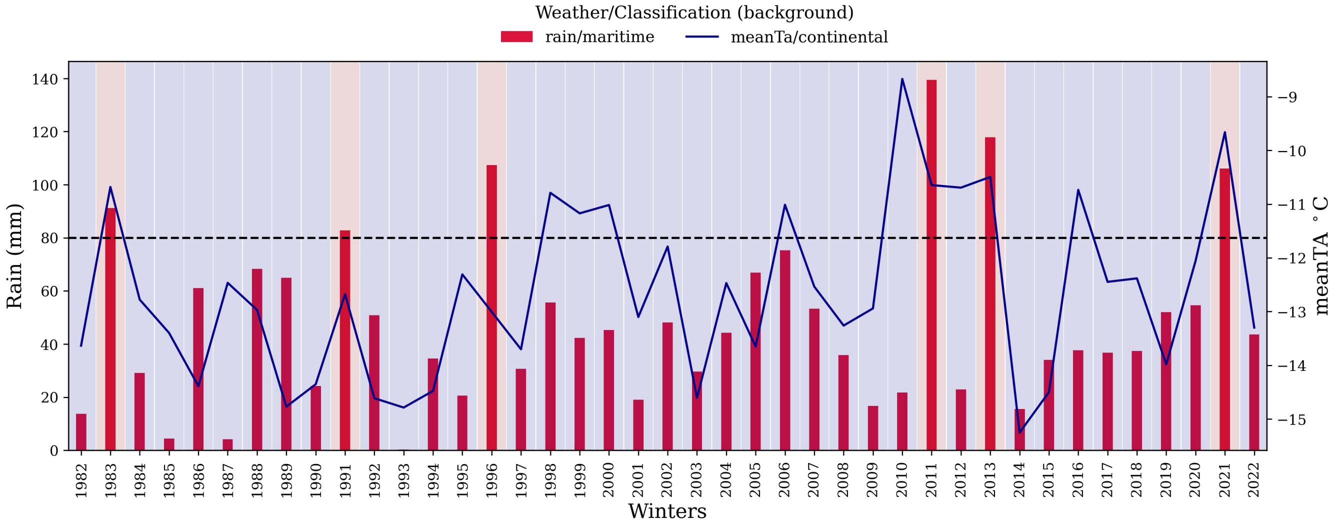

Fig. 3. Time series of the mean air temperature and total rain for the winter 1982 to 2022. The result of the Mock and Birkeland (2000) classification is shown with background color for each winter: the blue color is a continental classification, red is for maritime, transitional was never present). The mean air temperature is shown in dark blue and the total rain during the winter is shown in dark red. The black dashed line the 80 mm rain threshold for the maritime classification.

far from the -3°C threshold for a maritime winter. Some winters have been classified as maritime (7/40), and these winters are spread over the entire 40-year period. Despite the generally cold temperatures, rain events occur almost systematically every winter. Rain on snow event during the winter, combined with cold air temperature (meanTA $<$ -7°C) are the two main characteristics that define the region's snow climate.

Global Comparison

To compare our data with potentially similar locations around the globe, we adapted the boxplot figure from Mock and Birkeland (2000). First, we look at the two critical criteria used by the Mock and Birkeland (2000) algorithm for classification, which were meanDEC above 10°C m^{-1} (continental) and Rain above 80 mm (maritime) (Mock and Birkeland, 2000). These two criteria were in similar ranges to those for the Chic-Chocs, Central Japan, and Mt. Washington (Figure 4). The SWE, snowfall, and December temperature gradient for Central Japan were more comparable to the Chic-Chocs. The amount of precipitation was similar in all areas: Chic-Chocs, Central Japan, and Mt. Washington (Figure 4). We also compared all three areas to the three classic snow climates of the western United States (Mock and Birkeland, 2000). Snow-related parameters such as SWE, snow depth, and December temperature gradient were within the

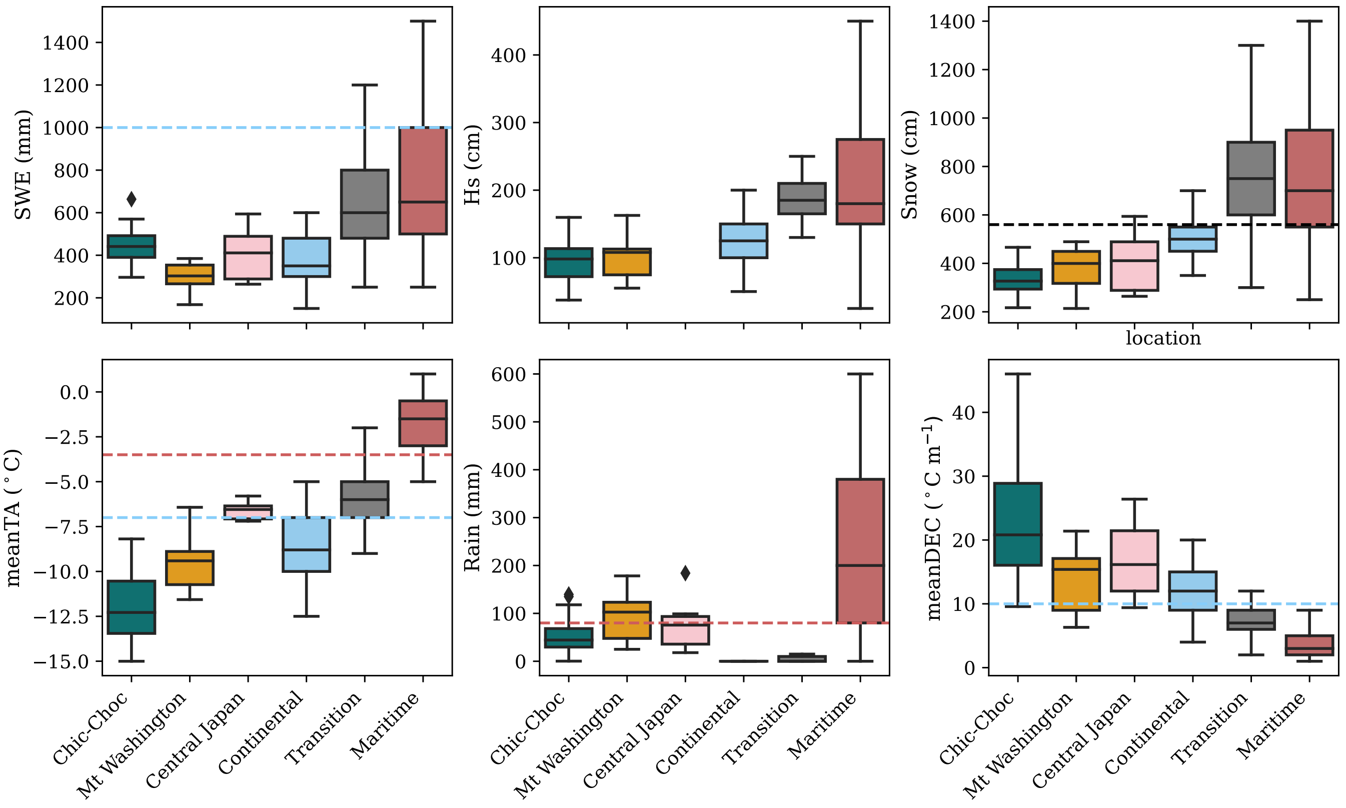

Fig. 4. Box plot with all the Mock and Birkeland (2000) climate classification for a global comparison with the Chic-Chocs dataset, Mt Washington from Meloche (2019), Central Japan from Ikeda and others (2009).

range for a continental snow climate (Figure 4). Air temperature was also within the range for a continental climate, with the Chic-Chocs and Mt. Washington at the colder end and Central Japan at the warmer end (Figure 4). Precipitation was the only determinant that fell within the Maritime snow climate range for all regions. These results indicate that all regions, Chic-Chocs, Mt. Washington, and Central Japan, were similar to the continental snow climate, except for precipitation, where they were similar to a maritime snow climate (Figure 4).

Snow grain type

We compared the frequency of the grain types simulated in SNOWPACK using CRCM6 model with snow profile observations from 2015 to 2018. Figure 5 shows a systematic discrepancy between observations and the simulated data. SNOWPACK tends to simulate melt forms (MF) more frequently than they are observed. Conversely, the simulation results seem to under-represent decomposing and fragmented particles (DF). The presence of rounded grains (RG) and precipitation particles (PP) is similar between

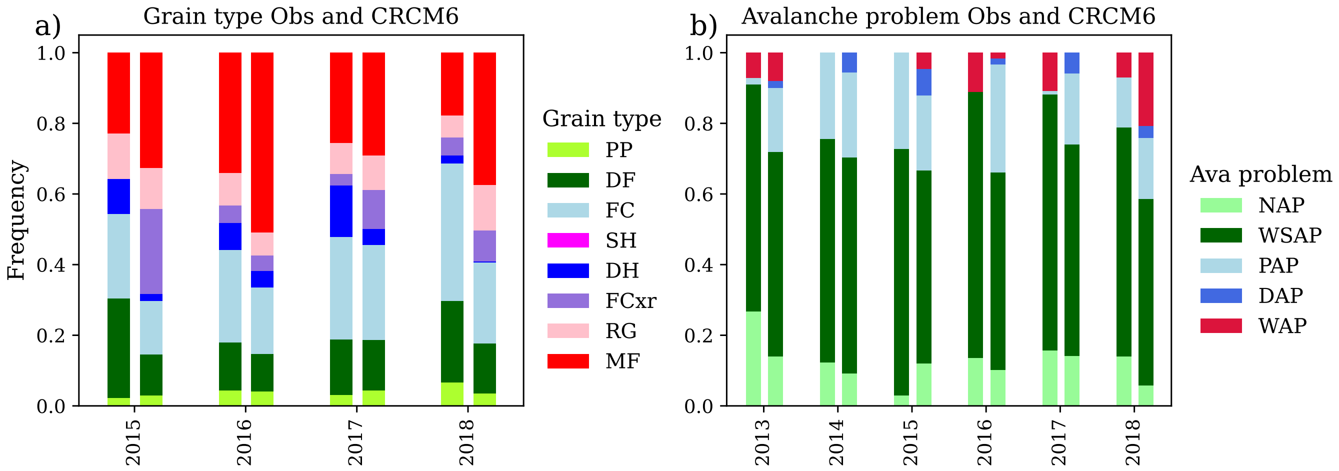

Fig. 5. Comparison of the observations vs the simulated (CRCM6/SNOWPACK) for a) snow grain type distribution, and b) Avalanche problem frequency. The left barplot is the observations from Avalanche Québec and the right barplot is the climate simulation CRCM6 dataset. The avalanche problem type are the following : New snow avalanche problem (NAP), wind slab avalanche problem (WSAP), persistent avalanche problem (PAP), Deep persistent avalanche problem (DAP), and wet avalanche problem (WAP).

the simulation from the model chain CRCM6/SNOWPACK and the observations. The faceted crystals (FC) are more often observed in the snow profiles, but the faceted rounded grains (FCxr) are more frequent in the simulation from the model chain CRCM6/SNOWPACK. However, these grain types are similar and represent a similar transformation process in the snow cover. Finally, depth hoar (DH) was more frequent in the snow profiles. Despite the small difference between the simulations and the observations, the model chain CRCM6/SNOWPACK is relevant to retrieve the seasonal snow grain type distribution.

The snow grain type distribution was retrieved from the 40-year SNOWPACK model to get an overview of the temporal variability in metamorphic process of the study area. First, the snow grain type shows that melt forms (MF) are predominant in the snow cover from December to the end of March (Figure 6-a). The second most frequent grain type are rounding faceted grains (FC). However, Figure 6-a shows that there is a temporal variability between winters, with some winters having more FC than MF. The third and fourth most abundant grain types were faceted crystals (FCxr) and rounded grains (RG). The presence of these two grain types was quite variable between winters, sometimes with more FCxr than RG and sometimes vice versa (Figure 6-a). Surface hoar was not present in the snow cover during the entire 40-year period. Overall, the 40-years of seasonal grain type distribution demonstrated different dominant metamorphic processes that should impact the dominance of specific avalanche problem types (i.e. persistent vs wet

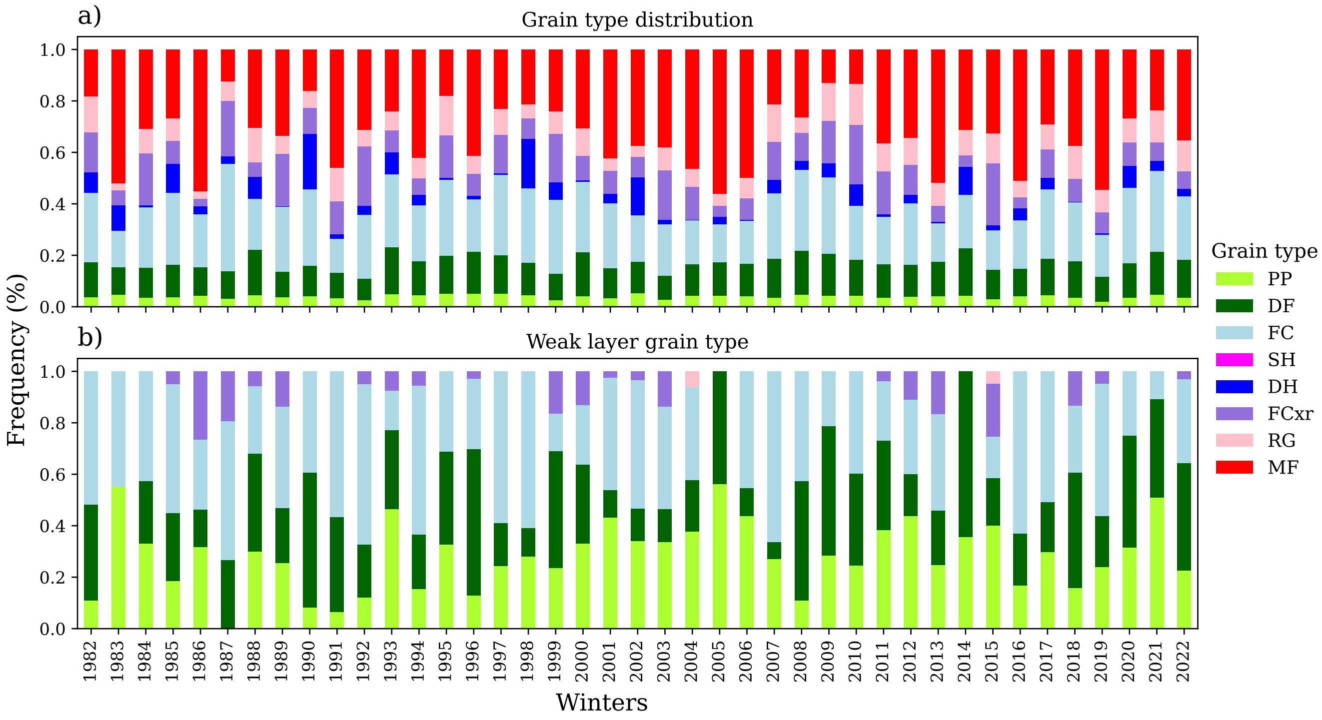

Fig. 6. Snow grain type distribution over the 40 winters period with a) snow grain type distribution of the whole snow cover each winter from December to the end of March, and b) the snow grain type distribution of the weak layer assessment for each winter (natural instability).

avalanche problem type).

The snow grain type distributions are different if looking at critical weak layers from the avalanche problem assessment (Figure 6-b). The three most common weak layer grain types are precipitation particles (PP), decomposing and fragmented particles (DF), and faceted crystals (FC). Like the overall grain type assessment, the most frequent weak layer grain type was not the same from winter to winter, where sometimes DF and PP were more frequent over FC, and some other winters the opposite occurs where FC was more frequent. It is important to note that this assessment is based on a weak layer with natural instabilities, and the frequency might change with including skier triggering. Some winters also had the FCxr in the weak layer assessment and two winters had few weak layers with RG as grain type. It is important to note that during the simulated 40-year period neither DH nor SH were present in the critical weak layers.

To explore the "typical" stratigraphy of the study area, two examples of simulated snow profiles (38 ° north facing slope) for Maritime and Continental winters are presented in Figure 7. The 'continental' winter of 2018 included a large rain event on 13 January (35 mm), which initiated a wet instability cycle for the next 10 days (Figure 7-a). After this event, however, colder conditions returned, with snow depths continuing to increase with several layers of FC, up to a maximum snow depth of 240 cm. These cold conditions persisted until the end of March. The "maritime" winter of 2021 had a large rain event (25 mm), which occurred on 25 December with a thinner snow cover (43 cm) and caused the snow cover to melt almost completely (Figure 7-b). The rain event delayed snow accumulation, resulting in a shallower snow cover compared to the continental winter of 2018. Despite the difference in amount and timing of the rain event in both winters, the resulting stratigraphy was quite similar and more representative of a continental snow cover with a thick melt-freeze crust in the basal layers, with FC above and DF/PP at the surface. The rains at the end of March were the main cause of this so-called maritime winter. This sequence of meteorological and different layers leads to a specific type of avalanche problem during the winter. In the following section, the winters of 2018 and 2021 are described in more detail in terms of avalanche problem type.

Avalanche problem type

Continental vs Maritime winter

Figure 7 shows the timing of avalanche problem types during the continental winter of 2018 and the maritime winter of 2021. The continental winter of 2018 had more natural instabilities compared to the maritime winter of 2021, with more significant storms producing more NAP, WSAP, PAP and DAP. The persistent problems (PAP/DAP) were more concentrated at the beginning of the winter, and the rain event of 13 January had removed the persistent weak layers. Surprisingly, the continental winter had more wet-snow instabilities (WAP) despite having less total rainfall during the winter (50 mm) compared to the maritime winter (93 mm). The persistent problems were concentrated towards the end of the winter in January, February and March. Regarding the avalanche problem type, the difference between the "maritime" and the "continental" winter was not significant and does not correspond to the definition of a maritime winter (more precipitation, less or no PAP/DAP).

Observations vs Simulations

We compared the seasonal frequency of predicted avalanche problem types from Avalanche Québec with those derived from snow cover modeling. In both cases, the most common avalanche problem type was wind slab avalanche problem (WSAP). Avalanche Québec generated slightly more WSAPs than the simulation

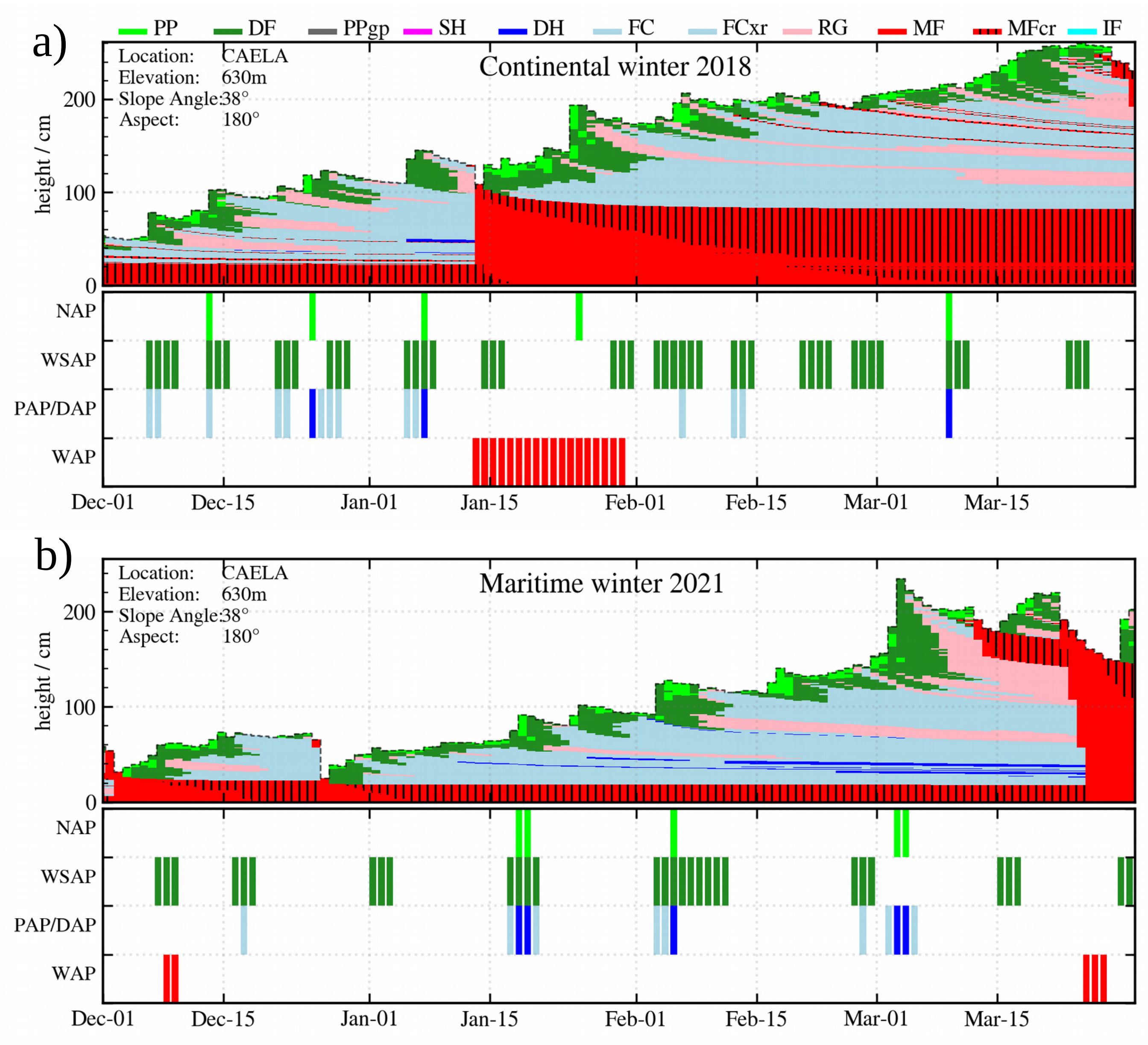

Fig. 7. Seasonal stratigraphy and avalanche problem type from the snow cover model output for a) an example Continental winter in 2018, and b) an example of a stratigraphy during the Maritime winter of 2021. New snow avalanche problem (NAP), wind slab avalanche problem (WSAP), persistent avalanche problem (PAP), Deep persistent avalanche problem (DAP), and wet avalanche problem (WAP).

from the CRMC6/SNOWPACK model chain. New snow problems (NAP) were more frequent compared to the simulation expected for the winter of 2015. Conversely, the persistent problem type (PAP) was also more frequent in the simulation compared to the Avalanche Québec forecast. Thus, NAP and WSAP were underestimated and PAP/DAP were overestimated by the CRCM6/SNOWPACK model chain. The winters of 2016 and 2017 were the most different between the simulation and the forecasts of Avalanche Québec, with no PAP/DAP and WAP (Avalanche Québec) compared to more PAP/DAP and almost no WAP (CRCM6/SNOWPACK). The (WAP) was the most variable between simulation and forecast. The deep persistent problem type (DAP) was never forecast by Avalanche Québec. These results show the systematic error or difference between the simulation and the forecast of the avalanche problem type, but we have to keep in mind that the significant differences could be related to the difference between the forecast guidelines (Avalanche Québec) and the numerical model (CRCM6/SNOWPACK).

40-year period

Figure 8-a shows the distribution of natural avalanche problem types that have occurred in our study area over the last 40 years. Four different avalanche problem types were present in the region, with the wind slab avalanche problem type (WSAP) being the most prevalent in the region. The second most frequent problem type was the persistent problem type (PAP) with an average of 13 days per winter and the deep persistent problem type (DAP) with an average of 3 days per winter. The wet avalanche problem type (WAP) was not present every winter with an average of 3.5 days/winter on a virtual northern aspect and 4.1 days/winter on a virtual southern aspect (Figure 7). The less frequent problem type was the new snow problem type with an average of 7 days per winter.

Figure 8-b shows anomaly over the 40-year period, with the colored background representing the classification by the Mock and Birkeland (2000) algorithm. The distribution of avalanche problems does not seem to be different for the maritime winter. The winters of 1991, 2011, and 2018 had the most WAP anomalies of the dataset, but the winters of 1991 and 2011 were classified as maritime and the winter of 2018 was classified as continental. However, other maritime winters appear to be the same as other continental winters without specific anomalies, such as winter (1996, 2013 and 2021) (Figure 8-b). These results indicate a possible limitation of the Mock and Birkeland (2000) algorithm and that the frequency of the seasonal avalanche problem type can give a different perspective on what could be a "maritime" winter.

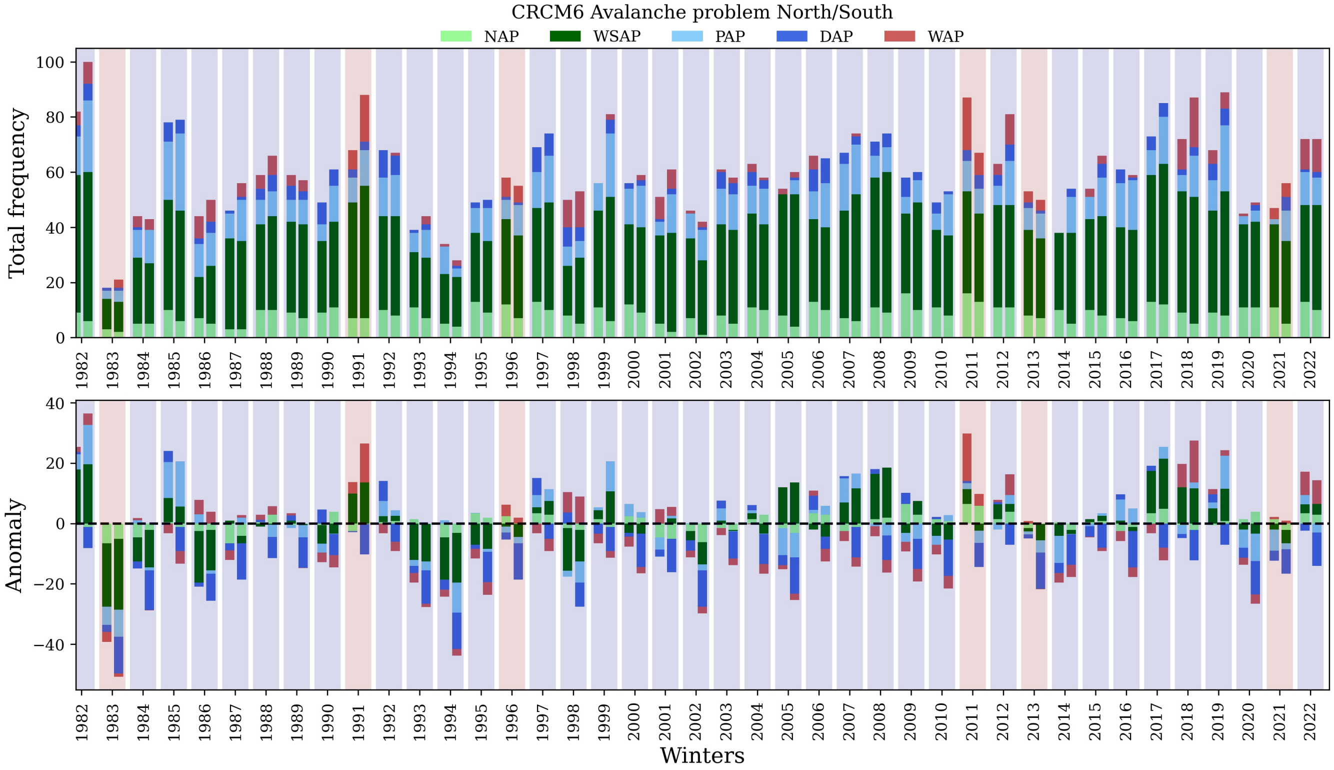

Fig. 8. Avalanche problem distribution for the winter 1982 to 2022, with the north face virtual slope on the left barplot and the south face on the right barplot. a) number of days where the problem type was issued, and b) the anomaly from the mean of the 40-year period. The blue colored background are winter classified as continental and the red is maritime. The avalanche problem type are the following : New snow avalanche problem (NAP), wind slab avalanche problem (WSAP), persistent avalanche problem (PAP), Deep persistent avalanche problem (DAP), and wet avalanche problem (WAP).

Clustering analysis

To get a new perspective on snow climate classification, we decide to look the clustering of the avalanche problem types. The result of the silhouette analysis shows that two clusters were the most significant for classifying the northern and southern simulation for the 40 winters, with an average silhouette score of 0.25 and a Calinski-Harasbasz score of 27.3. In close second, three clusters were also significant, with a silhouette score of 0.24 and a Calinski-Harasbasz score of 25.9. The remaining number of clusters (4,5,6..10) had decreasing Silhouette and Calinski-Harasbasz scores. Figure 9 shows the two and three clusters on a transformed dataset using Principal Component Analysis (PCA) to visually represent the clustering. The two clusters can be compared to a maritime and continental winters of the Mock and Birkeland (2000) algorithm. However, the seven maritime winters were in both cluster (2 in the blue and 5 in the red) (Figure 9). According to the vector variables of the PCA in Figure 9-c, the red cluster was characterised by more WAP and early WAP onset date (Decembre and January). By opposition, the blue cluster had more instabilities with all dry avalanche problem types and a late WAP onset date in April or later. These two clusters were quite different from the classic maritime/continental, with the blue cluster had more dry avalanche problem (NAP,WSAP, PAP/DAP). The only major difference between north and south aspect was that more NAP were simulated on northern aspect, and surprisingly, there was no significant difference in WAP or WAP onset date between aspect.

The three clusters that resulted from the analysis are presented in Figure 9-bd). The first cluster (red) was characterised by more WAP and early WAP onset date mostly in December. The second cluster (pink) was characterised by lowest NAP, WSAP and PAP/DAP with early to mid WAP onset date (January). The third cluster (turquoise) had the latest WAP onset date (April), and the lowest WAP. However, the maximum and the minimum values presented were relative to our dataset.

To compare our clusters with an other region, we present in Figure 10 our three clusters compared to the data of Reuter and others (2023), who cluster the avalanche problem type of the French alps. We compared the three clusters centroids of this present study with the four centroids founded in the French Alps. Two clusters had similar centroids between both studies, which were the pink clusters (cluster 1 and 5) and and the turquoise-green clusters (cluster 3 and 8) (Figure 10. The pink cluster in both studies had mid-season WAP onset date around February with a relatively low number of days with a persistent avalanche problem with 10 or less, and around 5 days of new snow problems, and the lowest days of wind slab problem. This cluster was observed, in the study of Reuter and others (2023), in the front ranges of

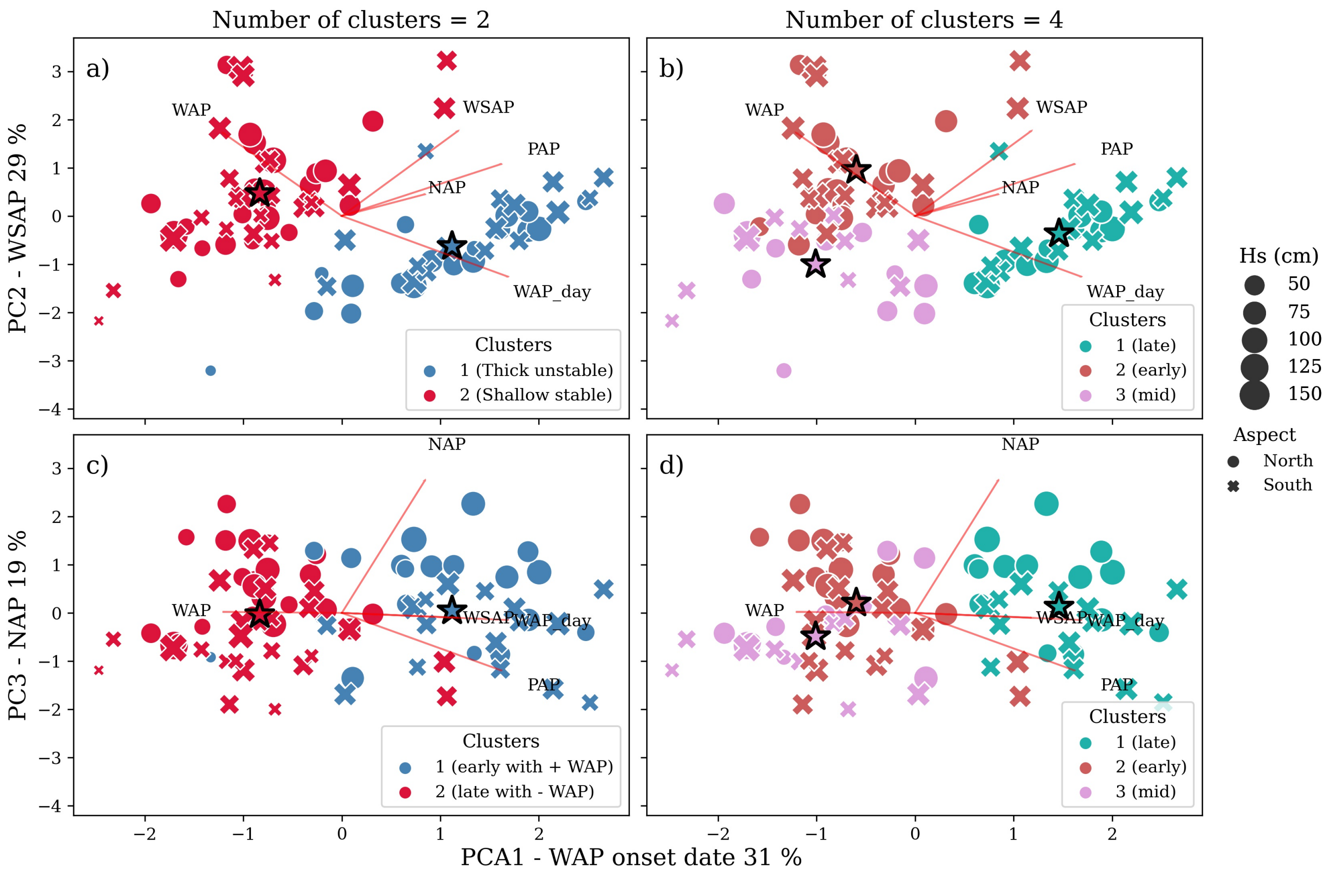

Fig. 9. K-means clustering with two and three clusters. The clusters are shown in relation to the principal component 1 (WAP onset date 31 %), principal component 2 (WSAP day 29 %), and the principal component 3 (NAP 19 %). The clustering with two clusters a) and c) demonstrates a new classification were winters were classified with a thick snow cover and unstable conditions, and other winters with shallow snow cover and stable conditions. The clustering with three clusters b) and d) demonstrates a different classification with snowy unstable winters, wet unstable winters and shallow snow cover and stable conditions.

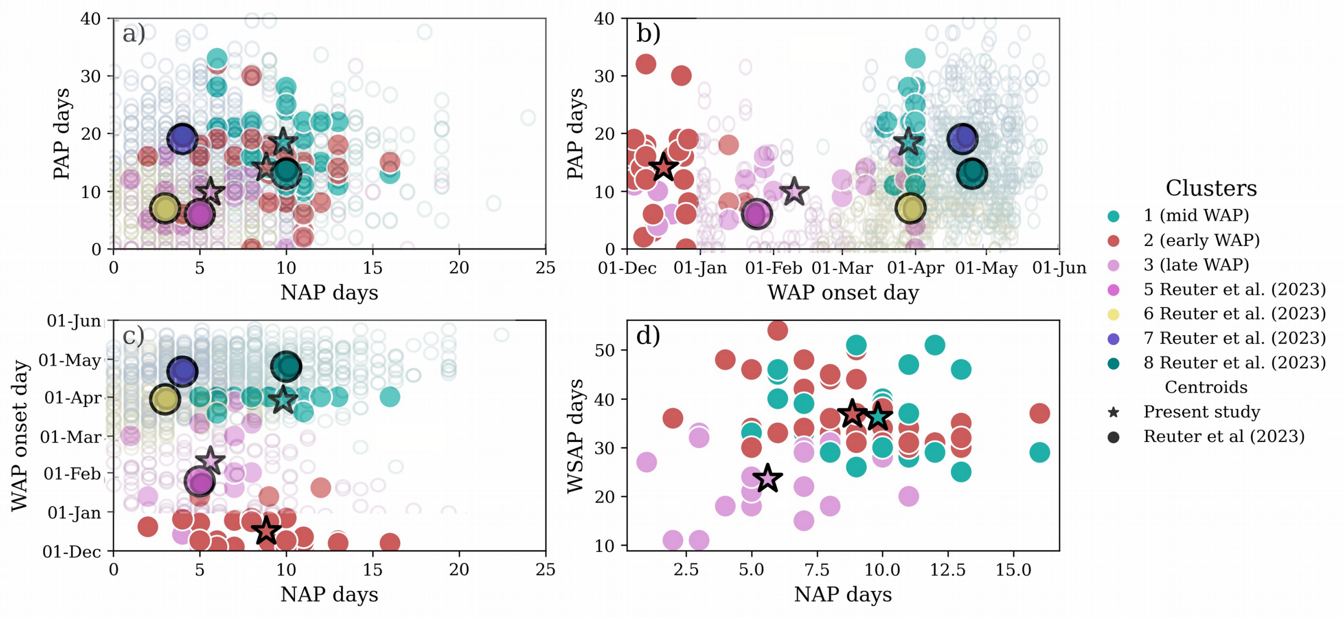

Fig. 10. Three clusters of this studies presented in comparison with the cluster centroids (cross) and the data in transparency of the study of Reuter and others (2023). The pink cluster of Reuter and others (2023) represents a cluster with low NAP, low PAP and a early WAP onset date before March. The green cluster of Reuter and others (2023) represents a cluster with high NAP, mid PAP and late WAP onset date after April. The yellow cluster ofReuter and others (2023) represents a cluster with high NAP, low PAP and mid WAP onset date around April. The purple cluster of Reuter and others (2023) represents a cluster with low NAP, high PAP and late WAP onset date around mid-April.

the French Alps, in regions like Vercors and Chartreuse, who classify mostly as "maritime" according to the Mock and Birkeland (2000) algorithm. The remaining cluster of this study (cluster 2 in red) does not fit with the other clusters from the Alps. Figure 10-bc shows the red cluster with a WAP onset date early during the season in December, which no cluster had such a early WAP onset date in the Alps. In terms of NAP and PAP days, the red cluster from our study was similar to the green cluster of Reuter and others (2023).

DISCUSSION

Can simulation data be used to classify snow climate?

This research provides an in-depth analysis of the snow and avalanche climate of the Chic-Chocs region, located in the northeastern Appalachian range in Canada. Through the use of climate indicators, snow grain types, and avalanche problem types, we aim to provide a comprehensive understanding of snow processes leading to avalanches in the region. Our dataset, derived from 40 years of CRCM6 climate simulation over North America, serves as a robust basis for simulating snow stratigraphy and avalanche problem types over this time period. This approach identifies snow cover characteristics relevant for avalanche situations. The use of snow cover modeling provides a new perspective on snow and avalanche climates in the region and complements the data available for snow and avalanche climatology.

Despite providing a significant temporal perspective, the model chain CRCM6-SNOWPACK simulations we show have inherent uncertainties stemming from the climate data or the snow cover simulations. To evaluate the performance of the CRCM6-SNOWPACK model chain, we present a comparison between observations and the simulation for the climate indicators (Table 1), snow grain types (Figure 5-a), and avalanche problem types (Figure 5-b). The uncertainties in the climate indicators and their classification, as described by Mock and Birkeland (2000), are mainly due to the classification of precipitation as rain or snow in both meteorological observations and CRCM6/SNOWPACK simulation. For example, the winter of 2013 was classified as continental in the meteorological observations but as maritime using the CRCM6 simulations, highlighting the discrepancies between the observations and the simulations with respect to precipitation events. Additional uncertainties arise from the precipitation gauge at the weather station, where snow accumulation on top of the gauge can prevent accurate measurement during rain.

The SNOWPACK model, in the current settings used in this study, has limitations that could affect the stratigraphy and thus the resulting uncertainty for avalanche problem types. As discussed in the previous section, the classification between rain and snow is also a limitation of the threshold used in the SNOWPACK model. We choose to use the default rain/snow threshold of 1.2 °C, which was empirically determined based on measurements in Switzerland. Bellaire and Jamieson (2013) simulated the snow cover in western Canada using numerical weather prediction of 15 km spatial grid, and tested different rain/snow thresholds to detect melt-freeze crust formation in Rogers Pass, Canada. The default threshold of 1.2 °C had the lowest probability of detection compared to other thresholds closer to 0 °C, which had a higher probability of detecting melt-freeze crusts. However, Madore and others (2022) simulated the snow cover in Roger Pass based on meteorological station and demonstrated that a threshold of 1.4 °C was better at simulating both melt-freeze crusts while a accurate estimation of the snow height. They also point out that this threshold was only found for the winter of 2018-2019, and that different winters could have a different threshold based on a different meteorological event (i.e., thermal inversion) or even different snow climate (Bellaire and Jamieson, 2013). This contrast between the results of Bellaire and Jamieson (2013) and Madore and others (2022) supports the argument that this threshold could be different depending on the meteorological context. Future work should focus on an effective way to find a adaptive rain threshold to simulate melt event and melt-freeze layer.

The second limitation is related to a snow density problem in both CRCM6 and SNOWPACK. With the correction of Imbach and others (2024), the estimation of SWE with average error of 54.5 mm, but with an underestimation of snow height. The relatively good estimation of SWE but underestimation of snow height could indicate a problem with the density of the new snow or the densification of the entire snow cover. We used Bellaire's new snow density parameterization, which is an empirical fit of new snow density based on several weather variables such as air temperature, wind speed, and relative humidity (Lehning and others, 1999). This parameterization is an empirical fit based on measurements in Switzerland, but may not be applicable in eastern Canada. Future work should investigate a different or new parameterization of new snow density that is better suited to the snow climate of eastern Canada. Despite introducing uncertainty in individual winter events, the CRCM6-SNOWPACK model chain was in good agreement at representing the seasonal average of climatic indicators, snow grain type, and avalanche problem type that represent well the snow climate of the region.

Snow and avalanche climatology

We applied the Mock and Birkeland (2000) algorithm to 40 winter using climatic indicators derived from the CRCM6/SNOWPACK model chain. 33 of the 40 winters were classified as continental and the remaining 7 winters as maritime. (Shandro and Haegeli, 2018) apply the (Mock and Birkeland, 2000) algorithm to three area in western Canada: The Coastal mountains (i.e. Whistler), the Columbia's mountains (i.e. Revelstoke) and the Rocky mountains (i.e. Banff). Comparing our snow climate classification results with the three areas in western Canada (Shandro and Haegeli, 2018), each of these three areas never had continental and maritime winters classified in the same area. The Coastal mountains only had maritime and transitional winter. The Columbia's mountains mostly transitional winters with some continental and maritime winters. The Rocky mountains only had continental winters and some transitional winters. Our study area is not similar to western Canada with had continental winters with some maritime winters. From the perspective of seasonal avalanche problem frequency, the Chic-Chocs region exhibits a distribution with around 10% of wet-snow problem types, around 10-20 % and the remaining is mostly wind slab and new snow problem type. This seasonal avalanche problem type frequency was similar to the Coastal Mountains (mostly maritime winters) and the Columbia Mountains (mostly transitional winters). Surprisingly, the Rocky mountains had mostly Continental winters like our study area, but the persistent problem type was more present around 60-70%, compared to 10-20% in the Chic-Chocs.

If we compared the climatic indicators of Mock and Birkeland (2000) algorithm with the three classic western region in the United-States, our study area shares similarities with continental regions for all meteorological variables except rain (Figure 4). Other regions of the world, such as Mt. Washington and the central Japanese Alps, exhibit the same pattern of low snowfall, cold air temperatures, and significant precipitation during winter (Figure 4). This suggests that the Chic-Chocs are also influenced by climate factors typical of the continental and maritime snow climates, resulting in snow climate characteristics that do not fit neatly into established classifications of western North America. The sequence from cold temperatures to significant rain is a distinguishing feature that sets these regions apart from classic snow climates of western North America. This dual influence results in snow cover that exhibit characteristics of both continental and maritime climates, such as the presence of faceted crystals and layers of ice due to rain-on-snow events. These mixed characteristics between a continental and maritime winters defined the specific climatic and snow coverconditions of regions such as the Chic-Chocs, Mt. Washington, and the Central Japanese Alps.

The snow grain type distribution and climatic conditions of the study area can be compared with those studied in Svalbard, Norway (Eckerstorfer and Christiansen, 2011). Both snow cover are cold and relatively thin ($\approx$ 1-1.5 m), dominated by temperature gradient metamorphism processes. These regions experience basal instability and faceted crystals due to cold winter temperatures, and are also affected by maritime depressions that bring warm air and rain, causing ice/melt freeze stratification in the snow cover. Similar to Svalbard, our results showed that the Chic-Chocs region has snow grain types characteristic of both a continental climate (facet and depth hoar) and a maritime climate (ice/melt-freeze layering). Snow and climate data revealed two major snow climate components: a cold snow cover combined with a maritime influence causing rain-on-snow events.

Ikeda and others (2009) described two study areas in the Japanese Alps: the Japanese Coastal Mountains (Northern Japanese Alps) and the Central Japanese Alps. Their research shows similarities between the Central Japanese Alps and the Chic-Chocs region. Both regions obtained similar snow climate results using the Mock and Birkeland (2000) flow chart: primarily continental winters with some maritime winters (Ikeda and others, 2009). The criteria used for classification are also similar, with a continental winter characterised by a mean December temperature gradient (meanDEC >10°C) and a maritime winter characterised by rainfall (> 80 mm) (Ikeda and others, 2009). The climatic conditions are similar, with cold air temperatures, low snowfall, and significant precipitation (Figure 4). The snow cover structures are comparable, showing a strong prevalence of faceted crystals and melt forms (Ikeda and others, 2009). The authors found that these characteristics did not fit any of the three major snow climate classifications, leading them to propose a new classification for the Central Japanese Alps: the Rainy Continental snow climate. This new classification is defined by the following specific characteristics (Ikeda and others, 2009):

1) A relatively thin snow cover and cold air temperatures, similar to continental snow climate regions.

2) Heavy rainfall, comparable to or exceeding that of maritime snow climate regions.

3) Persistent structural weakness caused by faceted crystals and depth hoar, similar to continental snow climate regions.

4) The dominance of both faceted crystals and wet grains.

Similar to Ikeda and others (2009), our results suggest that the snow climate of the Chic-Chocs does not fit into the three traditional snow climate classifications. Historically, the Chic-Chocs region has been classified as a maritime snow climate according to the Sturm and others (1995) global classification, which is based solely on climatic variables such as temperature and precipitation without considering snow cover or avalanche regimes (Sturm and others, 1995). Other authors have used the term Cold Maritime to describe the region (Fortin and others, 2011; Gauthier and others, 2017).

The Chic-Chocs region shares similarities with several regions around the world, such as Mt. Washington and the Central Japanese Alps. All of these regions are influenced by cold air masses from the continent and low-pressure cells from the ocean. These specific influences of both continental and maritime low-pressure cells have previously been observed for the northeastern coast of the United States (Karmosky, 2007; Perry and others, 2010). This contrasts with the coastal mountain ranges of the northwestern United

States, which are primarily influenced by maritime low-pressure cells. The four characteristics mentioned above for the Rainy Continental classification of the Central Japanese Alps are identical to those observed for the Chic-Chocs. However, the term "Rainy Continental" proposed by Ikeda and others (2009), expresses both continental and maritime influences, similar to a transitional snow climate. However, the term Rainy Continental could be a better fit for insular, peninsular, or northeastern continental regions than any of the three major snow climates developed for the larger mountain ranges of the western United States.

Recently, Reuter and others (2023) characterised snow avalanche climate regions in the French Alps by occurrences of avalanche problem types relevant for natural release. They applied the traditional snow climate classification of Mock and Birkeland (2000) and compared the results with a snow avalanche climatology based on a clustering analysis of avalanche problem type occurrences. Their analysis revealed 4 clusters defined by the number of days with persistent problems, the number of days with new snow problems and the onset date of wet-snow problems. These three factors lead to a combination of 7 possibilities, 4 of which they observed in the French Alps, with potentially three more based on their criteria. Based on our clustering analysis, two of our clusters were similar to two of the clusters observed in the French Alps. One cluster was similar to the one in the French Alps and has an average wet-snow activity onset date around February with a relatively low frequency of persistent weak layers (of around 8 days per season) and about 6 days with new snow problems. This cluster was observed in front-range regions on the western flank of the French Alps. A second cluster, similar to the Mont Blanc or the Beaufortain range in the French Alps, had a late wet-snow onset date around the end of April or later, around 13 days with persistent weak layers and 10 days with new snow problems per season. Our study revealed another cluster with a very early wet-snow onset date in December, but with similar frequencies of persistent and new snow problems.

Regarding climate change, Eckert and others (2024) reviewed the past and projected effects of climate change on avalanche activity. They found a significant decrease in dry snow avalanches relative to an increase in wet snow avalanches. Currently, more winters are characterised by dry snow situations, such as new snow, wind slabs, and persistent problem types, compared to wet-snow problem types. However, as shown by Eckert and others (2024), these proportions could change towards more situations with wet-snow relative to dry-snow avalanches problems. Giacona and others (2021) observed an upslope shift of avalanche activity, where low altitude mountains saw a reduction in the number and the period of avalanches. This finding suggests that clusters with late onset dates (April) of wet-snow avalanche problems are likely to be affected or disappear in favour of the other two clusters with a mid-season (February) and early wet-snow onset date (December). Today's Chic-Choc snow climate may correspond to the projection of snow climates in other regions, as the Rainy Continental may be the new Continental.

Perspective

Building on the framework developed by Reuter and others (2022, 2023), this study details and characterizes the snow and avalanche climate of the Chic-Chocs Range, located in the northeastern Appalachian Mountains of North America. The implementation of the avalanche problem type, derived from 40 winters of SNOWPACK simulations, provided a unique perspective to describe the snow and avalanche climate of the area. As suggested by Shandro and Haegeli (2018) and Reuter and others (2023), using the avalanche problem type introduces a new perspective to propose new classifications for regions that differ from the three conventional snow climates found in western North America. Unlike the geographic clustering study of Reuter and others (2023), our approach was temporal, aiming to identify different "types" of winters that the region may experience. Figure 9-bd illustrates a clustering into three categories over the 40 winters, differing from the continental and maritime 'types' of winters by primarily using the avalanche problem type. This type of research opens the possibility to characterize the snow and avalanche climate where field data are not available. The ERA5 climate model of the European Center for Medium-Range Weather Forecasts (ECMWF), coupled with the SNOWPACK simulation and the method of Reuter and others (2022), represents a new potential framework to analyze new regions that aim to create an historic of potential avalanche problem types to develop a forecasting system based on their climate.

CONCLUSION

This study provides a comprehensive analysis of the snow and avalanche climate in the Chic-Chocs region of the Gaspé Peninsula, as part of the northeastern Appalachians in eastern Canada. Using a variety of methods and data sources, including meteorological observations, snow grain type distributions, and avalanche problem types, we provide a detailed characterization of the region's specific snow and avalanche climate.

The snow climate classification results, based on the Mock and Birkeland (2000) flowchart, indicate a predominantly continental climate with occasional maritime winters. This finding contrasts with the more traditional snow climate observed in western North America, highlighting the specificity of the Chic-

Chocs region. Our comparison with similar regions around the world, such as Mt. Washington and the central Japanese Alps, revealed patterns of low snowfall, cold air temperatures, and significant rain precipitation. This similarity suggests that the Chic-Chocs, like these other regions, do not fit neatly into traditional classifications of continental, maritime, or transitional snow climates. Furthermore, comparison with Svalbard, Norway, underscored the presence of cold, thin snow cover dominated by faceted crystals and basal instability, influenced by both cold winter temperatures and maritime depressions. These conditions result in a snow cover structure characterised by both continental and maritime elements, such as faceted crystals and ice/melt freeze layers.

The inclusion of avalanche problem types derived from 40 winters of snow cover simulations (CRCM6-SNOWPACK) provided seasonal patterns of natural snow instability mostly dependant on the month where the wet-snow problem type occurs. We were able to compare our results with another study in the French Alps and discuss a classification/cluster exclusively around avalanche problem type, shifting from the traditional climate-based description. This study highlights the potential of snow cover modeling and avalanche problem type methodology to improve our understanding and classification of snow climates, ultimately contributing to improved avalanche forecasting and risk management in regions with similar complex dynamics. Finally, in our broader perspective of climate change, where rain and wet-snow problem type may become more common for continental regions around the world, the Rainy Continental of the Chic-chocs may be the new Continental around the world.

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