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Estimating winter trends in climatic variables in the Chic-Chocs Mountains, Canada (1970–2009)

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ABSTRACT: This paper presents an analysis of winter climate variability based on daily mean temperature and precipitation data since 1970 in the Chic-Chocs Mountain range (located in the Gaspé Peninsula, Eastern Quebec, Canada). Mountain environments are particularly sensitive to rapid climate change and are therefore good indicators of recent global warming. The main goal of this study is to demonstrate how joint probability temperature/precipitation distributions can be used to estimate winter condition changes (trends) for six meteorological stations in the study area (the altitudinal range for the stations is from 5 to 574 m). The presence and persistence of snow cover was also estimated. Previous studies have shown a lack of evidence of significant trends in snow-cover characteristics (density, depth and snow water equivalent (SWE)) from the early 1980s to the present, despite an increase in temperature over the same period. A reanalysis of these data sets in addition to the use of a combination of temperature and precipitation data categorized into four modes (warm/wet, warm/dry, cold/wet and cold/dry) was also performed. Despite this new analysis, no clear evidence of climate change could be found in the study area over the last four decades. The results revealed that patterns and trends are quite different from one station to another, but when the environment is taken into account (valley or plateau, coastal *versus* inland) some apparent patterns emerge.

KEY WORDS winter; climatic variables; trends; Chic-Chocs; Canada; precipitation; temperature; snow cover

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1. Introduction

Snow cover is a reliable indicator for detecting and monitoring climate change at different geographical scales. Two of the most common variables used to describe snow-cover variability through both space and time are duration and snow depth (Karl *et al.*, 1993). Snow duration is given by the number of days between the onset and the loss of the seasonal snow cover, and is important for mountain plants (Gottfried *et al.*, 2011). Snow-depth (or thickness) observations are useful for estimating the snow-cover extent. Moreover, surface air temperatures are also strongly correlated with the snow-cover extent (Groisman and Easterling, 1994). Air temperatures are useful in calculating the number of degree-thaw or freeze-thaw cycles (Seidel *et al.*, 2009; Fortin, 2010). These two climatic conditions cause snowpack instability. Precipitation, including both the total amount and the types (snow, rain or winter mix), is also significant because the ratio of rain to snow can modify the properties of the snowpack. Precipitation amounts and types are also sensitive hydrologic indicators of climatic variability (Huntington *et al.*, 2004).

Mountains and uplands are particularly sensitive to global warming (Beniston, 2003) and a better understanding of their complex ecosystems and climates is essential for a better management of these areas and for climate predictions more generally. The spatial variability of the snow cover is particularly complex in mountainous areas, where terrain factors modify the energy balance. Many recent studies of snow-cover variability over the 20th century in mountainous regions have observed changes. For example in the Swiss Alps, Beniston *et al.* (1997) found that the most affected areas by changes on snow cover since the 1940s are those that are located at altitudes lower than 1500–2000 m because the low to medium altitude areas are more prone to a rapid melt when the temperature goes above freezing. Etchevers and Martin (2002) obtained similar results in the French Alps, demonstrating that lower altitude areas are most likely to be affected by future warming. Fyfe and Flato (1999) also noted that the warming is enhanced at higher elevations over the Rocky Mountains. By contrast, Petkova *et al.* (2005) found no evidence of long-term trends linked to climate warming for the Bulgarian mountains between 1931 and 2000. These differences illustrate the contradictory nature of climate change as it affects different mountain climates.

In general, the low temperatures at higher elevations help keep the snow cover in place, and by a retroactive effect the snow cover, with its high albedo, can decrease

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air surface temperatures by more than 5 °C (Burakowski *et al.*, 2008). Winter precipitation and the snow cover on other mountainous areas have been studied recently in the Northeastern United States (Durkee *et al.*, 2008; Huntington *et al.*, 2004; Seidel *et al.*, 2009) and in Eastern Canada, including the Gaspé Peninsula (Hétu, 2007; Fortin and Hétu, 2009; Fortin and Hétu, 2010; Fortin *et al.*, 2011). From these studies, it is clear that the northeastern mountains have been affected by recent climate warming, but it is not clear if this is the case for the Chic-Chocs. The geographical and geomorphological context of the Chic-Chocs range (coastal *vs* inland, valley *vs* plateau) can explain a significant part of the climate variations, as we will see in the following sections. Cogbill and White (1991) have shown that geography can, in some cases, be the main factor explaining vegetation distribution patterns in the northeastern Appalachian Mountains. On a large scale, however, the teleconnection patterns can explain some of the changes in temperature, precipitation and snowpack variability. Particular attention will be paid in this paper to five of them, respectively: the North Atlantic Oscillation (NAO, probably the most important), the Arctic Oscillation (AO), the Southern Oscillation (SO), the Pacific/North American Pattern (PNA) and the Atlantic Multidecadal Oscillation (AMO). These oscillations are all recognized as having a great influence on the winter climate in the Northeastern US and Southern Canada (Brown, 2010).

Recent studies of the Chic-Chocs Mountains have used proxy data (permafrost: Gray *et al.*, 2009; Putnam and Putnam, 2009; alpine vegetation: Cogbill and White, 1991; Fortin and Pilote, 2008; tree rings: Boucher *et al.*, 2003; Dubé *et al.*, 2004; Germain *et al.*, 2009) to assess the influence of global change on a finer scale. Brown (2010) has closely studied snow-cover variability in the province of Quebec and found both the presence of latitudinal gradients and also the influence of some oscillations (for example, NAO) depending on the geographical locations. However, this latter study was done at the scale of a very large region, and only two of his snow courses are located on the Gaspé Peninsula. Otherwise, little information about the cold season climate is available for the region, in large part because of the harsh conditions on the highest summits of the study area. The significant decrease in the number of national weather stations since the end of the 1960s, compounded by a problem of missing data for many weather stations, also limits analysis for the region. The winter climate of the Chic-Chocs Mountains was well documented by Gagnon (1970) for the 1940–1969 period, when 47 weather stations were operational (including 30 automatic and 17 observer-manned stations). Although some of the stations provided data for only a few years, many covered the entire period. In fact, the strengths of Gagnon's study contributed to our decision to focus on the period since 1970.

The main goal of this study is to evaluate whether trends for daily mean temperatures and total daily precipitation can be detected for the cold season (from 1st December until 30th April) in the Chic-Chocs Mountains since the early 1970s. We used 'winter' in a broader sense than the astronomical season. In this study, March (when the snow depth reaches its maximum) and April (the main snowmelt period) are considered to be winter months. We applied a joint temperature/precipitation modes approach as proposed by Beniston (2009) and López-Moreno *et al.* (2011), in order to detect trends based on various scenarios (cold/wet or CW, cold/dry or CD, warm/wet or WW, warm/dry or WD).

We also investigated the correlations between these modes, variables and five climatic indices (NAO, AO, SO, PNA and AMO) because, at a regional scale, geographic factors (mountainous areas) and climate factors (teleconnections) can also greatly influence the snow-cover variability. For example, snowfall amounts over the southern limit extension of the Chic-Chocs should be tied to the NAO teleconnection pattern. Hartley (1999) found that the south and central Appalachians region show a significant inverse relationship with the winter index of the NAO: more snowy winters occurred during the negative phase of the NAO and precipitation fell mostly as rain when the NAO phase was positive (Durkee *et al.*, 2008). While no previous work has been carried out specifically on the influence of climate oscillation and the snow cover for the Chic-Chocs area, Germain *et al.* (2009) have identified a number of critical climatic conditions that contribute to the triggering of high-magnitude avalanches. These conditions include an above-average total snowfall, a higher frequency of snowstorms, major rain events and facet-crust development as well as sequences of freezing rain and strong winds. These climatic conditions can also be influenced by atmospheric patterns such as NAO, AO, SO, PNA and AMO. Similarly, Assani *et al.* (2006) assessed the influence of four of these patterns (all except for the AMO) for 70 hydrologic stations in southern Quebec between 1970 and 1995. These results not only showed how the atmospheric patterns influenced precipitation fluctuations, but also emphasized that different river flow phases had even greater influence. Thus, changes in the frequency, intensity and location of these atmospheric patterns could impact the sensitive mountain snowpack and ecosystems of the Chic-Chocs region, but other factors must also be considered (Fortin and Hétu, 2010).

2. Study area

The Gaspé Peninsula is located in the southeastern part of the Canadian province of Quebec (Figure 1). The peninsula is bordered on the north and east by the Gulf of St Lawrence and by the Chaleur Bay to the south. The Chic-Chocs Mountains are part of the Appalachian range that begins in Georgia (USA) and extends towards the ENE to the Long Range Mountains in Newfoundland. The regional topography of the Gaspé Peninsula can be divided into three main units: the McGerrigle Mountains, the Mont Albert massif and the Chic-Chocs Range. The highest summit is Mont Jacques Cartier (1268

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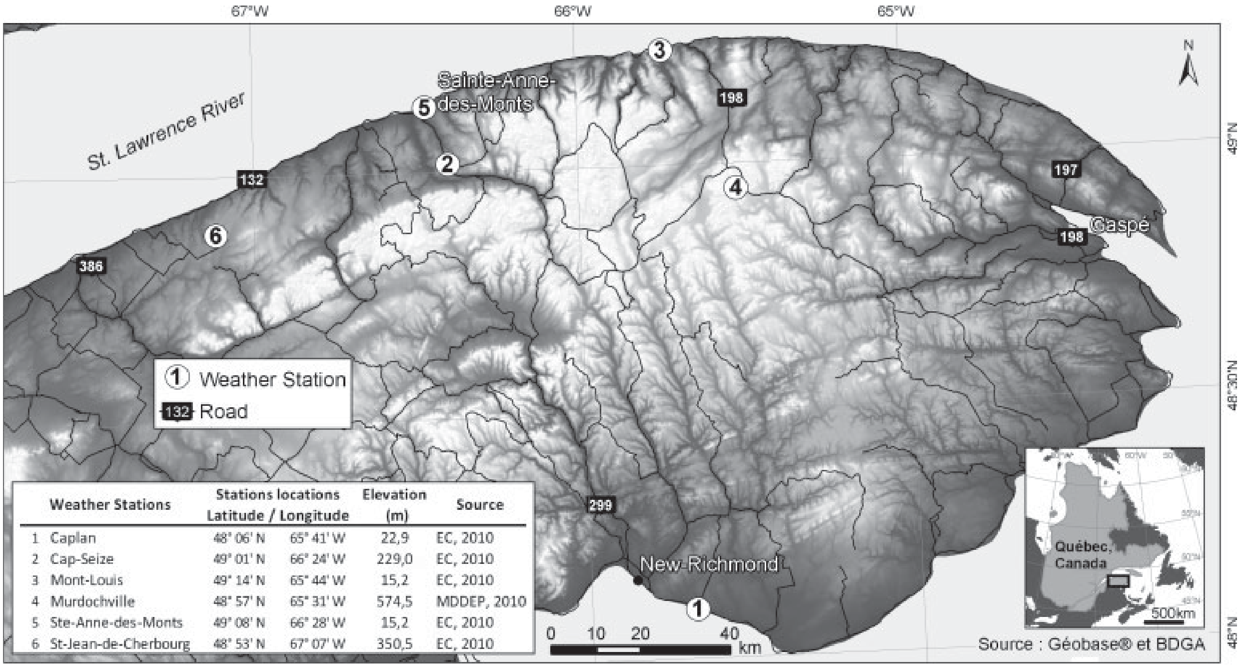

Figure 1. Location of the Chic-Chocs Range and weather stations used in this study (mapping: Marie-Andrée Roy).

a.s.l.), located within the McGerrigles. Boudreau (1981) has delineated its vegetation into three zones: a mountain forest up to 900–975 m, a subalpine area continuing up to 1110 m and an alpine area extending to the summit. Different climate (wind, snow depth, solar radiation, etc.) and soil conditions (the presence of permafrost, soil composition, water saturation) influence the distribution of the vegetation. Although no meteorological station is located at the summit, Gray and Brown (1979) used soil temperatures between −3 and −5 °C (for the period 1970–1979) to estimate the mean annual air temperature. Gray *et al.*, 2009 extended the measurements (1979–2008) and redid the calculation, confirming that the previous estimation remained valid for the period after 1979.

Limited snowpack and meteorological data have been published for this region because of its lack of accessibility. Gagnon (1970) examined snowpack variability in the Chic-Chocs Mountains for the period from 1940 to 1969, while Boudreau (1981) focused only on the summit of Mont Jacques Cartier during the first half of January 1973. These experts had other research objectives and so did not apply their results to larger questions of climate change.

3. Data and methods

The data for this study obtained from the daily weather database (temperature, precipitation and snow depth) from provincial (Ministère du Développement Durable, de l'Environnement et des Parcs or MDDEP, one station: Murdochville) and national (Environment Canada or EC, five stations: all the remaining) networks for a winter period extending from December 1st through April 30th (Figure 1). Snow data sets from snow courses taken every 2 weeks from the onset until the complete meltdown of the snowpack by the MDDEP at four different sites from 1980 to 2009 have already been studied in detail by Fortin and Hétu (2010).

3.1. Weather and snow data

We applied a number of control procedures in order to ensure the quality of the data. We verified that no major changes occurred that might disrupt the continuity of the findings, such as the relocation of a weather station, and we further checked for suspicious or missing data, filling any gaps with estimated data extrapolated from the surrounding stations. It is sometimes possible to use incomplete series to do certain statistical tests if the proportion of missing data is relatively low. For example, Haylock *et al.* (2008) have used a threshold of up to 20% of missing data (for temperature and precipitation) to decide which weather stations would be retained for their study. They then proceeded to estimate the missing data. We chose to do the same, although using two different methods. The first method replacing our missing data by a weighted-mean of the annual trend of the weather stations as following:

$$P_x = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\overline{P_x}}{\overline{P_i}}P_i\right) \tag{1}$$

where, P_x is the estimated missing precipitation or temperature data; n the number of reference stations; P_i the precipitation or temperature at the reference station i; $\overline{P_x}$ the long-term mean precipitation or mean temperature at the station x and $\overline{P_i}$ the long-term mean precipitation or mean temperature at the reference station i.

The second method was used to validate the first. This method is described in detail by Laborde and

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Mouhous (1998). It takes into account the effects of altitude (z), in addition to those of the distance (x, y) between the stations. Because the amount of missing data in our time series is relatively limited, our results indicate very little difference between the values obtained by the two methods. It therefore seems that the first method is justified in the context of our study. It is important, however, not to generalize from this case, because while the two methods provide comparable results in our study, this might not be the case for other types of mountain environments with higher altitudes or other differences.

The missing values needed to be estimated because complete data sets are required to calculate the total number of days that can be classified in each of the four modes (CD, CW, WD and WW). Underestimating the days for one or more classes because of missing data could lead to misleading or incomplete results. Fortunately, the data from other stations can reliably be used by applying formula (1).

The first variable examined was daily snow depth, which was recorded automatically by the weather stations. The snow-cover duration can be calculated by the time between the median date of snow-cover onset and disappearance. We used the Environment Canada definition from 2010 (Environment Canada, 2010) which states that the median date of snow-cover onset is the first date followed by 14 consecutive days of snow cover >2 cm in depth. Similarly, the median date of snow-cover loss is the last date preceded by 14 consecutive days of snow cover >2 cm in depth. This method imposes a maximal limit of 150 days for snow cover, between December 1st and April 30th. The snow thickness corresponds to the monthly mean snow depth.

With regard to the different temperature/precipitation modes, we first had to determine the threshold values that corresponded to the 25 and 75% quantiles that are the basis of the mean daily temperature and total precipitation amounts. These thresholds are different for every weather station. The 25 and 75% quantiles are defined as follows: for the temperature, either cold (if temperature is below 25% quantile, T_{25}) or warm (if temperature is above the 75% quantile, T_{75}) and for the precipitation, either dry (if precipitation is below 25% quantile, P_{25}) or wet (if precipitation is above 75% quantile, P_{75}). Different thresholds could be used, for example, if we wanted to retain only the extreme events, we could use 10 or 90%, on the other hand, it would have been possible to use thresholds as generous as 40 and 60% (López-Moreno *et al.*, 2011), in order to get an idea of the events located slightly above or below the average. Although more extreme or moderate thresholds might be applied, we retained 25 and 75%, as used by Beniston (2009), because this allowed us to properly represent the majority of important events and distinguish larger trends. The temperature (T) and precipitation (P) values for each day were compared to these thresholds. Results between 25 and 75% were excluded, while results above or below one of the thresholds were classified into one of the four modes: Cold/Dry (CD) if T_{25}/P_{25}; Warm/Dry (WD) if T_{75}/P_{25}; Cold/Wet (CW) if T_{25}/P_{75} and Warm/Wet (WW) if T_{75}/P_{75}. We could then analyse the frequency of each mode over a month, a winter or a decade.

The next step was to investigate possible correlations between the frequency of the modes and the five atmospheric patterns (NAO, AO, SO, PNA and AMO). We took the values for each oscillation from the winter standardized indices available from the NOAA website (http://www.cpc.ncep.noaa.gov/data/).

3.2. Statistical tests

We next applied statistical tests to ensure that our results were significant. A number of nonparametric rank-based statistical tests for detecting monotonic trends in time-series data have been identified. We considered two possibilities, the Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975), which is particularly common in hydrometeorological studies, and the rarer Spearman's rho test (Lehmann and D'abrera, 2006; Burakowski *et al.*, 2008; Yue *et al.*, 2002). Yue *et al.* (2002) compare these two tests to assess their respective power and show that both tests give similar results when certain conditions apply. As these conditions applied to our data (for example, we verified that there was no auto-correlation in the data that could bias our results), we chose the more common MK test. The $x_1, x_2, \ldots, x_n$ are the data points where x_j represents the data value at time j. The MK statistic S is given by

$$S = \sum_{k-1}^{n-1} \sum_{j=k+1}^{n} sgn\left(x_j - x_k\right) \quad (2)$$

where,

$$\text{sgn}\left(x_j - x_k\right) = \begin{cases} 1 \text{ if } x_j - x_k > 0 \\ 0 \text{ if } x_j - x_k = 0 \\ -1 \text{ if } x_j - x_k < 0 \end{cases} \quad (3)$$

The value of S is an indicator of the trend (high or low) either positive or negative. But the probability associated with S and the sample size (which should be greater than 10 with very few ties) should be calculated to evaluate the statistical significance of the trend. In accordance with Kendall (1975) the normal-approximation test for the distribution of MK S can be performed by calculating S first, followed by the calculation of the variance of S, VAR(S) (Equation 4), the computation of the standard normal test statistic Z (Equation 5) and finally of the probability associated with the normalized test statistic (Equation 6).

$$\text{VAR}(S) = \frac{\left\{ n\left((n-1)\,(2n+5) - \sum_{p-1}^{g} t_p\left(t_p - 1\right)\left(2t_p + 5\right) \right) \right\}}{18} \quad (4)$$

where n is the number of data points, g is the number of tied groups and t_p is the number of data points in the pth

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group.

$$Z = \begin{cases} \frac{S-1}{[\mathrm{VAR}(S)]^{1/2}} \text{if } S > 0 \\ 0 \text{ if } S = 0 \\ \frac{S+1}{[\mathrm{VAR}(S)]^{1/2}} \text{if } S < 0 \end{cases} \tag{5}$$

$$f(Z) = \frac{1}{\sqrt{2\pi}} e^{\frac{z^2}{2}} \tag{6}$$

After calculating the trend by using the MK test, we used Sen's nonparametric estimator of slope, a method of estimating the trend magnitude over time within the data (Gilbert, 1987). When the data shows an upward slope, there is evidence of an upward trend. The Sen's slope estimator is the median of all pair wise slopes in the data set, calculated as follows (Sen, 1968):

$$\beta = \mathrm{Median}\left(\frac{x_j - x_i}{j - i}\right) \tag{7}$$

To complete the analysis of our time series, we used the Pettitt test (Pettitt, 1979), another nonparametric test based on the Wilcoxon test where the rank of the values of the sequence is used. The Pettitt test is useful because it identifies the presence of a change point (called *inflection point* in the sequence d_i) in time series (under the alternative hypothesis). Otherwise, under the null hypothesis, the test assumes that the annual values of the testing variable are independent and identically distributed (Winjngaard *et al.*, 2003). The Pettitt test is particularly appropriate for determining the homogeneity of monthly, seasonal or annual-resolution climatic time series. The Pettitt test can be calculated using the following equation (Fraedrich *et al.*, 2001):

$$X_p = 2R_p - p\ (n+1) \tag{8}$$

where p is the position within the series d_i, n is the number of values of the series and R_p is the sum of the ranks of the series d_i of the values.

4. Results and discussion

Our principal results are the frequency of the temperature/precipitation modes described in the previous section. The descriptive statistics of the daily mean temperature and total precipitation, for all the stations used in this study, are shown in Table 1. The coldest temperatures and the highest precipitation amounts were recorded at the higher elevation sites (Murdochville and St Jean). Meanwhile, coastal and valley stations (for example, Mont-Louis and Ste Anne) had the lowest temperature amplitude (low standard deviation or SD) and the lowest total precipitation. The Cap-Seize station had the highest SD for temperatures and the highest mean total precipitation. The latter results are exceptional because of the geographical location of the station – in the bottom of a valley (Ste Anne River) and far enough inland to escape the maritime effects of the St Lawrence River. In general, the stations can be divided into two groups; the valley and plateau characterized by lower mean temperature (−8.5 to −8.7 °C) and more mean daily precipitation (2.6 to 3 mm/day) and the coastal stations with a milder temperature (−5.7 to −6.6 °C) and less precipitation (1.9 to 2.3 mm/day).

4.1. Climate trends

As described in Section 3, the temperature/precipitation modes were calculated for six stations. The modes frequency (equivalent to the total number of days for each mode) are presented (y axis) with respect to time (x axis) for the entire period from 1970 to 2010 in Figure 2. Each of the four modes (WW, WD, CW and CD) showed different patterns that changed through time and over space. We could not identify significant trends in these changes because of the high inter-annual variability in the results. We also applied the MK test to each of the modes, and found no significant trends for any of the modes (auto-correlation has been checked in our data set before applying the MK test to avoid the false trends). However, while it is true that the magnitude of the frequency varied from one station to another, in general, the direction of change (increase *versus* decrease) for all the stations seems to follow a similar pattern. Table 2 gives an overview of the mean frequency for each mode per decade since 1970. This latter table confirms that no significant trend occurred over time within any of the modes from 1970 to 2010. Thus, our research results are different from those of studies of European mountain areas; these studies did find significant trends related to climate change (Beniston, 2009; Beniston *et al.*, 2011; López-Moreno *et al.*, 2011).

Beniston *et al.* (2011) have observed, for four stations in the Swiss Alps, a higher number of modes and also a greater SD especially for the WD mode than what we found in our study area (36.3 for the Swiss Alps *vs* 20.8 for the Chic-Chocs). This difference can be partly explained by a colder climate in the Chic-Chocs and the relatively lesser elevation difference between our six stations. In general, winter temperatures are colder in Gaspé than in the Alps. Temperatures closer to the freezing point make the Alps more sensitive to changing modes of atmospheric circulation. The WD mode, for example, is supposed to have the most significant negative impact on the snowpack (by reducing the amount of snow on the ground and the duration of snow cover) but for our study area this occurs less frequently. Another factor that might explain the lower frequency of the WD mode in the Chic-Chocs is related to the method we used to discriminate between the different modes. This method is based on the highest and lowest percentiles (75th and 25th), which means that in a climate with smaller differences between the highest and lowest values, temperatures are more centred around the mean. This could explain why the values presented in Figure 2 and Table 2 were below what have been reported in Europe (note that no similar calculations have been carried out for other parts of northeastern North America).

Despite the lack of evidence of a significant trend for all modes, our research results are more conclusive when

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Table 1. Descriptive statistics for the six weather stations.

		Min.	Max.	Mean	Std Dev.
Caplan	Mean temp. (°C)	−27.0	15.8	−5.7	6.9
	Tot. prec. (mm)		70.4	2.3	5.4
Cap-Seize	Mean temp. (°C)	−29.8	20	−8.5	8.1
	Tot. prec. (mm)		70	3.0	5.6
Mont-Louis	Mean temp. (°C)	−29.0	19.5	−6.1	7.0
	Tot. prec. (mm)		76.2	2.2	5.2
Murdoc.	Mean temp. (°C)	−31.1	18.5	−8.5	7.4
	Tot. prec. (mm)		67	2.7	5.6
Ste Anne	Mean temp. (°C)	−26.1	18.3	−6.6	7.0
	Tot. prec. (mm)		76.2	1.9	4.1
St Jean	Mean temp. (°C)	−31.5	15.3	−8.7	7.8
	Tot. prec. (mm)		58.4	2.6	5.0

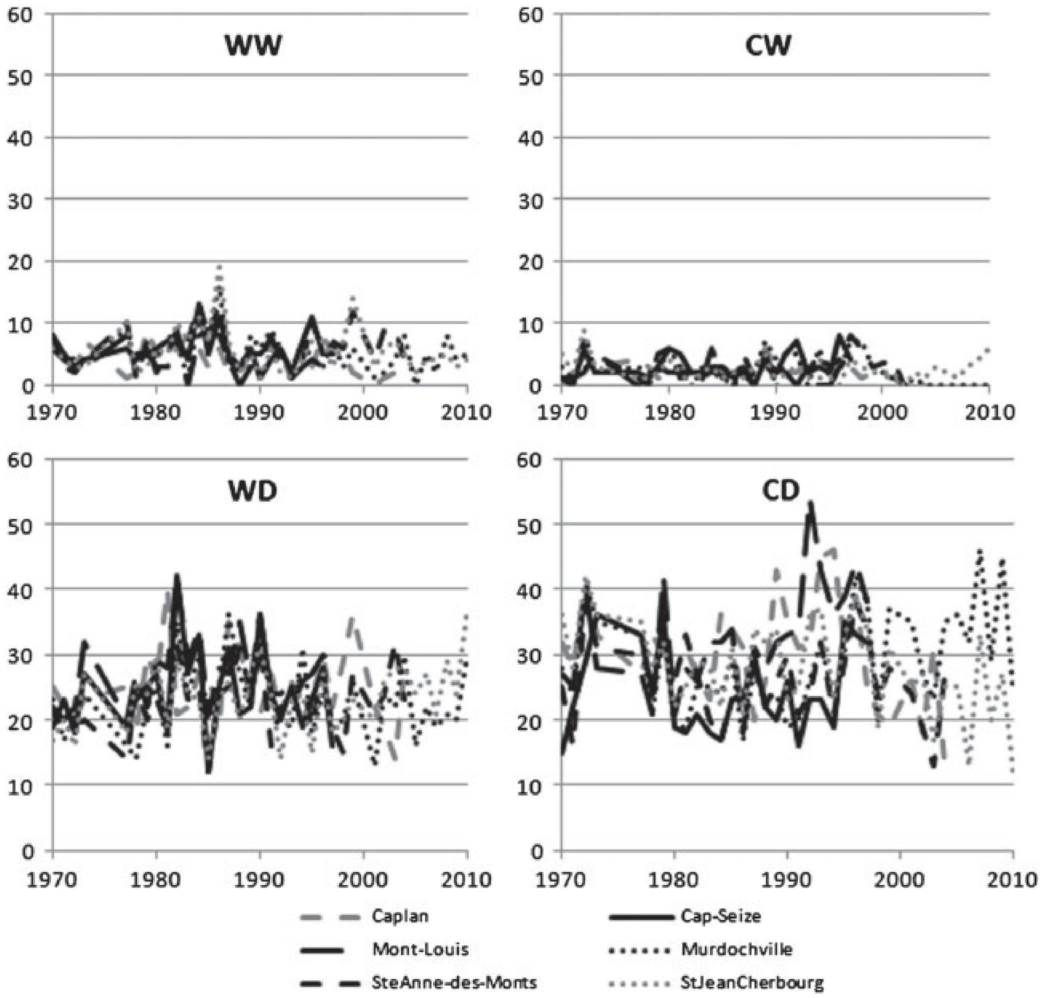

Figure 2. Variability of each mode (CW, WD, CD and WW) for the six sites. The modes frequency (y axis) and years (x axis) are shown.

we consider mean temperatures and total precipitation separately. Once again using the MK test for each time series, some significant trends can be observed for certain variables at different moments during the winter, as shown in Table 3.

Firstly, we expected to observe an increase in mean temperature during the winter, notably during the coldest months (January and February), as has been observed by Burakowski *et al.* (2008) for the nearby northeastern United States. However, none of our stations showed significant trends for January and only one did so for February (Cap-Seize) and, in fact, the trend was negative, that is, the mean temperature diminished over time. The only station showing a significant warming trend over the entire study period was St Jean for April. With regard to total precipitation, we expected to see a decrease in snow cover, as found by Brown and Mote (2009) for the Northern Hemisphere over the past four decades.

Table 2. The four modes [Cold/Dry (CD) if T_{25}/P_{25}; Warm/Dry (WD) if T_{75}/P_{25}; Cold/Wet (CW) if T_{25}/P_{75}, Warm/Wet (WW) if T_{75}/P_{75}] observed during the study period (mean values are for the six stations).

Mean/decade	CD	CW	WD	WW
1970–1979	25.7	2.9	19.8	4.9
1980–1989	23.6	2.4	21.5	5.5
1990–1999	26.2	2.5	21.3	5.1
2000–2009	23.6	2.0	20.8	4.8
Mean (1970–2009)	24.8	2.5	20.8	5.1
SD	1.2	0.3	0.7	0.2

Once again, however, the trends in our results were few and limited, as shown in Table 3. Only the station of Murdochville reported a significant trend (decrease) for a significant number of months (every month except for January). This suggests that the overall decrease in total precipitation found by Brown and Mote (2009) only affected the highest altitudes of our region. In any case, the lack of other weather stations at a similar or higher elevation restricts us to a speculative hypothesis. In fact, all of the other significant trends recorded were positive, indicating an increase in total precipitation (Table 3). These results conform to modelled expectations over the coming decades (Hayhoe *et al.* 2007), as well as findings reported for parts of the US Northeast (Moore *et al.*, 1997; Trombulak and Wolfson, 2004) including mountainous areas (Hodgkins and Dudley, 2006; Seidel *et al.*, 2009). Once again, however, firm conclusions are impossible because few stations showed significant changes over the study period (1970–2010). The spatial variability could not easily explain the differences, and the trends that we found are not consistent. Two stations (Caplan and Ste Anne) showed no significant trend over the winter either for temperature or for precipitation. The fact that these are coastal stations reminds us that the local environment, in this case the coast, can influence the effects of climate change.

Another way that geography influences the degree of climate variability is general weather patterns. For example, the study area is located in the eastern part of Quebec where different winter storm tracks often merge. Some of the most important systems include the Mackenzie Low, Alberta Low, Colorado Low and Gulf Low (Conrad, 2008). Each of these systems results in different weather conditions, for example, Colorado Lows (which have their origin in the state of the same name) move towards the northwest and pass over the Great Lakes allowing the warm air and moisture load to build up and bring heavy snowfalls winter to southern Quebec including the Gaspé Peninsula. Two other low-pressure systems (Hatteras Low and Great Lakes Low) can occasionally deviate towards the north and affect the Gaspé Peninsula. While these two systems are less common, they can cause severe winter conditions, especially when the cold dry air arrives from the Arctic and opposes the warm moist air of the Gulf Stream. This creates a strong thermal gradient resulting in severe winter conditions (blizzards, snow storms, etc.). During winter, a slight reinforcement of either low or high pressure can modify the synoptic patterns that control regional weather and thus modify the precipitation (rain or snow) and temperature (above or below the freezing point). The location of the Gaspé Peninsula at a 'tipping point' may thus partially explain both the shift in the weather during the winter and the high inter-annual variability that have been observed over the past four decades.

Another factor that could mask the evidence of climate change is the phases of teleconnections mentioned above, particularly if they are not synchronized. If one teleconnection is in a positive phase and another is in a negative phase this may reduce or cancel the effects of one or the other. This synergy between the different teleconnections complicates the respective influence that can be assigned to each of them. For example, the AMO, whose cycle is a period of between 65 and 80 years, could conceivably obfuscate the evidence for climate change. This is important because the AMO was positive (warm phases) during 1940–1960 period and again recently, but it was negative (cold phases) from the early 1970s through to the mid-1990s (Enfield *et al.*, 2001). Another example of the inter-relationship between teleconnections and their impact occurred in 1976 when the SO, NAO and AO were in a positive phase while the PNA and AMO were in a negative phase. Their interactions led to instability and the frequent subsequent phase changes considerably affected air masses, storm activities and storm tracks. Further research is needed on these synoptic-scale processes because of their influence on snow cover.

In addition, we evaluated the magnitude of the trends by using the Sen's slope estimator (Table 4). This revealed that the total precipitation for January at the Cap-Seize station showed the strongest (3.49) change over the time. Positive trends were also obtained for January at stations Mont-Louis (1.14) and St Jean (0.93). Meanwhile, the highest negative value for precipitation in December was recorded at the Murdochville station (−2.37). This same station indicated that the trends obtained for precipitation are statistically significant (obtained via the MK test) and negative for all other months except for February. Low magnitude negative (−0.11) is also observed for the temperature in February in Cap-Seize station.

We also applied the Pettitt test to mean temperatures and total precipitation, with the addition of other variables (daily minimum and maximum temperature, rain, snow and snow depth) to investigate whether the trends are continuous or characterized by an inflection point in the slope (Table 5). With regard to mean temperature, we detected few homogeneities – Mont-Louis and Ste Anne stations in March and Murdochville station in December. Similarly, only three homogeneous series were detected for minimum temperature, all occurring in March (Cap-Seize, Mont-Louis and Ste Anne weather stations). The highest homogeneity (23.3%) was discerned for maximum temperature. Only the month of February was

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Table 3. Mann–Kendall test statistic (S) and (Z).

Months	Var.	Caplan		Cap-Seize		Mont-Louis		Murdochville		Ste Anne		St Jean	
		(S)	(Z)	(S)	(Z)	(S)	(Z)	(S)	(Z)	(S)	(Z)	(S)	(Z)
Dec.	T	0.12	1.02	−0.01	0.00	−0.05	−0.33	0.08	0.73	0.19	1.57	0.20	2.03
	P	−0.10	−0.80	0.15	1.00	−0.27	−1.85	**−0.43****	−3.90	−0.04	−0.31	0.11	1.36
Jan.	T	−0.03	−0.26	−0.05	−0.30	−0.13	−0.91	0.00	0.06	0.24	1.80	0.21	2.27
	P	0.12	0.94	**0.39****	2.69	**0.29***	2.03	−0.17	−1.51	0.20	1.57	**0.23***	2.28
Feb.	T	−0.20	−1.51	**−0.28***	−1.94	−0.23	−1.56	−0.06	−0.45	0.03	0.16	0.14	1.65
	P	0.07	0.45	0.11	0.72	0.07	0.44	**−0.26***	−2.40	0.06	0.44	0.13	1.00
Mar.	T	−0.18	−1.25	0.03	0.07	−0.07	−0.44	−0.19	−1.69	0.08	0.16	−0.02	0.15
	P	−0.08	−0.77	0.03	0.21	−0.23	−1.61	**−0.31****	−2.78	0.01	0.44	0.02	−0.27
Apr.	T	0.04	0.23	0.20	1.38	0.29*	1.94	−0.06	−0.59	0.21	1.52	**0.25***	2.23
	P	−0.18	−1.59	−0.07	−0.49	−0.07	−0.44	**−0.22***	**−1.97***	−0.08	−0.63	−0.14	−1.27

Var.: Variables where T is temperature and P is precipitation. S and Z: trends are assessed to be statistically significant at the significance level of 0.05 if $p \leq 0.05$ and at 0.01 if $p \leq 0.05$. Bold values are significant values either at 0.05 (*) or at 0.01 (**).

Table 4. Magnitude of the trends estimated by the Sen's slope estimator (Q).

Months	Var.	Stations					
		Caplan	Cap-Seize	Mont-Louis	Murdoc.	Ste Anne	St Jean
Dec.	T	0.06	−0.00	−0.03	0.03	0.10	0.08
	P	−0.62	1.13	−1.01	**−2.37**	−0.18	0.65
Jan.	T	−0.01	−0.02	−0.05	0.00	0.07	0.08
	P	0.71	**3.49**	**1.14**	−0.74	0.79	**0.93**
Feb.	T	−0.06	**−0.11**	−0.14	−0.02	0.01	0.05
	P	0.22	0.80	0.48	**−0.86**	0.22	0.27
Mar.	T	−0.06	0.01	−0.04	−0.05	0.01	0.01
	P	−0.54	0.25	−1.36	**−1.70**	0.22	−0.13
Apr.	T	0.01	0.07	0.07	−0.01	0.04	**0.05**
	P	−1.11	−0.60	−0.54	**−0.95**	−0.35	−0.47

Bold values are those for which the MK test is significant.

inhomogeneous for all six stations. In general, precipitation results were more homogenous for both the total amount of rain (56.6%) and snow (50%). Some stations showed slight differences between the forms of precipitation. For example, Murdochville station recorded homogenous results for total rain in December and January, but not for total snow and total precipitation.

Next, we investigated whether correlations could be found between the four joint temperature-precipitation modes discussed previously and snow duration and snow thickness. The four modes are strongly tied to snow-cover variability, which means that the probabilities of finding strong correlations should be high. However, the results (Table 6) show that only two modes (WD/thickness and WW/duration) correlated at more than one station (Ste Anne and St Jean for the first and Caplan and Mont-Louis for the latter). Other modes are correlated to various degrees with only one of either snow duration or thickness and only at a single station. These results make any conclusion about correlations between the four modes and snow-cover duration and depth dubious.

Finally, we investigated whether snow-cover duration and thickness were correlated with five atmospheric patterns. We identified five key atmospheric patterns (NAO, AO, SO, PNA and AMO) that could have influenced both precipitation and temperature in the Chic-Chocs area. All results are shown in Table 6. The results with regards to the mode, snow duration and thickness were similar, indicating that it is difficult to clearly identify the influence of one or many dominant climatic indices. The strongest correlations were obtained for the Cap-Seize (−0.59 for PNA/duration) and Mont-Louis (−0.54 for AO/duration) stations.

A strong correlation between temperature and the extent of snow cover in the Northern Hemisphere has already been shown by Groisman and Easterling (1994). Similarly, Brown and Goodison (1996) reconstructed Canadian snow cover for the period of 1915–1992 and found no evidence of statistically significant long-term trends in snow cover in any of the regions studied. They showed, however, that small changes (<10% of the snow-cover area over a century) occurred in southern Canada, where snow cover had increased during winter but decreased in spring. Their results also showed that Canadian snow cover is characterized by considerable inter-annual and regional variability, something we also found for the winter climate of the Chic-Chocs Mountains. Such variability has been reported in studies of other parts of the globe; for example, Moberg *et al.* (2006) for Europe. A particular challenge with this variability is that it is difficult to establish the impact of teleconnection patterns on snow cover – these patterns vary greatly in time and space. Just as Brown and Petkova (2007) have not found any evidence of climatic change

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Table 5. Pettitt test (data homogeneity)[a].

Variables	Caplan					Cap-Seize					Mont-Louis				
	D	J	F	M	A	D	J	F	M	A	D	J	F	M	A
Max. temp.	□	□	□	□	●	●	●	□	□	□	□	□	□	□	□
Min. temp.	□	□	□	□	□	□	□	□	●	□	□	□	□	●	□
Mean temp.	□	□	□	□	□	□	□	□	□	□	□	□	□	●	□
Tot. rain	●	□	□	●	●	●	●	●	□	□	●	●	●	□	□
Tot. snow	●	□	●	●	●	●	●	●	●	□	□	□	□	●	●
Tot. prec.	●	□	●	●	●	●	●	●	●	●	□	□	●	□	□
Variables	Murdoc.					Ste Anne					St Jean				
	D	J	F	M	A	D	J	F	M	A	D	J	F	M	A
Max. temp.	□	□	□	□	□	□	●	□	●	□	□	●	□	●	□
Min. temp.	□	□	□	□	□	□	□	□	●	□	□	□	□	□	□
Mean temp.	●	□	□	□	□	□	□	□	●	□	□	□	□	□	□
Tot. rain	●	●	●	□	□	□	●	●	□	□	●	●	●	□	□
Tot. snow	□	□	●	□	□	●	●	●	●	□	□	□	□	□	□
Tot. prec.	□	□	●	●	□	●	●	●	●	□	□	□	□	□	□

[a]Confidence interval of 99% around the p-value; ● = homogeneous or □ = non homogeneous.

Table 6. Correlations (Pearson's r) between the four joint temperature-precipitation modes, the four climatic indices and snow duration and average snow thickness.

	Caplan	Cap-Seize	Mont-Louis	Murdoc.	Ste Anne	St Jean
CD/duration	0.14	−0.26	−0.38	0.11	0.05	**0.41**
CD/thickness	0.05	−0.08	−0.18	−0.09	0.00	0.31
CW/duration	−0.07	−0.06	0.27	0.05	**0.46**	0.12
CW/thickness	−0.22	0.07	**0.41**	0.30	0.30	−0.28
WD/duration	−0.35	**−0.52**	0.20	−0.13	−0.10	−0.19
WD/thickness	0.29	−0.05	−0.02	0.14	**−0.41**	**−0.46**
WW/duration	**0.42**	0.26	**0.52**	−0.12	−0.34	0.00
WW/thickness	0.07	−0.21	**0.63**	−0.05	0.14	0.19
NAO/duration	0.23	−0.14	−0.34	−0.05	0.09	−0.10
NAO/thickness	0.33	0.02	−0.27	0.08	0.23	0.03
AO/duration	0.31	0.30	**−0.54**	−0.02	0.22	−0.08
AO/thickness	0.39	0.16	−0.23	0.03	0.24	0.04
SO/duration	0.30	0.31	0.06	−0.01	**0.44**	0.07
SO/thickness	0.13	0.13	0.21	0.08	−0.13	0.06
PNA/duration	−0.25	**−0.59**	0.27	0.07	**−0.45**	0.15
PNA/thickness	−0.10	−0.24	−0.24	0.03	−0.19	−0.14
AMO/duration	−0.38	0.06	0.26	−0.19	0.00	−0.16
AMO/thickness	−0.17	**0.48**	0.24	−0.08	0.08	−0.27

Bold values are significant either at 95% level (above 0.4) and at 99% (above 0.5).

on the mountain snow cover in Bulgaria, we could not for the Chic-Chocs mountains area.

5. Conclusions

This paper provides an overview of the winter climate for a mountainous part of southeastern Canada where few previous studies of recent climate variability have been undertaken. Although few significant trends were found for temperature, precipitation and snow (duration and thickness) some important conclusions nevertheless emerged:

- Precipitation (rain, snow, total) series are clearly more homogeneous, in accordance with the Pettitt test, through the study period than temperature series (min. max. and mean). Significant variability is observed among the stations and for those where the time series are inhomogeneous this could mean that at a certain point there was one or many ruptures (changes) in the trend.
- Winter climate for the study area is poorly correlated with the five following atmospheric patterns: NAO, AO, SO, PNA and AMO and follows a different pattern than what has been reported for the Northeastern United States and southern Quebec.
- There are few trends that apply over the entire study period for all of the climatic variables used in this study, and some of them are contradictory. It seems, however, that at the highest station (Murdochville) the total amount of precipitation is strongly affected by the recent slight increase in temperature. The stations located in the valleys or plateau have shown the lowest mean temperature and highest precipitation amount received by contrast to the coastal stations that recorded milder temperatures and less precipitation.

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Recently Fortin and Hétu (2012) investigated whether the ratio of snow to precipitation changed over the last four decades, as had been observed by Huntington *et al.* (2004) for the northeastern United States, but found no such change in the Gaspé Peninsula. This investigation represents another way to determine how global warming affects the Chic-Chocs Mountains and the Gaspé Peninsula. Our results indicate the importance of further study of different regions in order to better understand how climate change manifests and how other factors, such as geography and weather patterns, influence that manifestation.

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