UNIVERSITÉ DU QUÉBEC

MÉMOIRE PRÉSENTÉ À
L'UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

COMME EXIGENCE PARTIELLE
DE LA MAÎTRISE EN SCIENCES DE L'ENVIRONNEMENT

PAR
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ANALYSE STATISTIQUE DE LA VARIABILITÉ TEMPORELLE CONJOINTE DE LA TEMPÉRATURE ET DES PRÉCIPITATIONS HIVERNALES AU QUÉBEC MÉRIDIONAL

JANVIER 2015

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AVANT-PROPOS

Le présent mémoire a été réalisé sous la direction du professeur Ali Assani et la codirection du professeur Mhamed Mesfioui. Il est rédigé conformément à l'article 138.1 du *Règlement des études de cycles supérieurs* permettant de présenter les résultats obtenus dans le cadre d'une maîtrise de recherche en sciences de l'environnement sous forme d'un ou plusieurs articles scientifiques.

Ce mémoire est constitué de trois chapitres. Le premier correspond à une mise en contexte de la problématique du sujet d'étude ainsi que la synthèse des méthodes et résultats présentées dans les chapitres II et III. Par conséquent, certaines répétitions peuvent survenir entre les trois chapitres. Le deuxième et le troisième chapitre sont présentés sous forme d'articles scientifiques. Ces derniers ont été traduits et soumis à des revues scientifiques spécialisées pour publication, où je suis première auteure.

L'article qui constitue le second chapitre de ce mémoire a été soumis dans la revue *International journal of climatology* (Nadjet **Guerfi**, Ali A. **Assani**, Mhamed **Mesfioui,** Christophe **Kinnard)** sous le titre : « Comparison of the temporal variability of winter daily extreme temperatures and precipitations in southern Quebec (Canada) using the Lombard and copula methods ».

Conception et idées de recherche : A.A, N.G

Formulation des objectifs et hypothèses : N.G, A.A

Analyse des données : N.G, A.A, M.M, C.K

Résultats et discussion : N.G, A.A, M.M, C.K

Écriture de l'article : N.G, A.A

L'article qui constitue le troisième chapitre (Nadjet **Guerfi**, Ali A. **Assani**, Raphaëlle **Landry**, Mhamed **Mesfoui)** « Analysis of the joint link between extreme temperatures, precipitation and climate indices in winter in southern Quebec using a new canonical correlation analysis approach » a été soumis dans la revue *Theoretical and applied climatology.*

Conception et idées de recherche : A.A, N.G

Formulation des objectifs et hypothèses : N.G, A.A

Analyse des données : N.G, A.A, R.L, M.M

Résultats et discussion : N.G, A.A, R. L, M.M

Écriture de l'article : N.G, A.A

REMERCIEMENTS

La rédaction de ce mémoire n'aurait été possible sans l'intervention de certaines personnes. Qu'elles trouvent ici l'expression de mes plus sincères remerciements.

Je tiens tout d'abord à remercier vivement mon directeur de recherche, monsieur Ali A. Assani, de même que mon-codirecteur de recherche, monsieur Mhamed Mesfioui pour leurs conseils précieux et leurs directives durant la réalisation de cet humble travail.

Merci aux professeurs Jean-François Quessy et Christophe Kinnard d'avoir accepté d'apporter un jugement sur ce travail.

J'aimerais aussi remercier mon amie Raphaëlle Landry pour l'aide qu'elle m'a apportée dans les analyses statistiques.

Merci à Catarina Leote Franco Pio pour son aide dans la mise en page du document.

Je tiens enfin à remercier tout particulièrement ma famille qui m'a accordé la patience nécessaire pour réaliser ce travail ainsi que toutes les personnes qui m'ont soutenue.

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CHAPITRE I

INTRODUCTION

1.1 Mise en contexte

Le climat du Québec est caractérisé par des hivers très froids et très neigeux. En Amérique du Nord, c'est la seconde région qui reçoit la plus grande quantité de neige (entre 200 et 300 cm en moyenne par an) après les Rocheuses (Dorsaz et Brown, 2008). Les précipitations neigeuses jouent un rôle primordial sur le cycle de l'eau, sur le fonctionnement des écosystèmes fluviaux et leur évolution morpho-biologique ainsi que sur l'activité socio-économique. Sur le plan hydrologique, la fonte de la neige hivernale génère des crues printanières et recharge les nappes phréatiques qui alimentent les rivières pendant les périodes d'étiage en été et en hiver même (p. ex. Assani et Tardif, 2005; Larocque et Pharand, 2010; Nastev *et al.*, 2005). En ce qui concerne les débits de rivières, plus de la moitié de l'écoulement annuel survient au printemps au moment de la fonte de la neige au Québec (Assani et Tardif, 2005). Quant à l'alimentation des nappes aquifères, à titre d'exemple, une étude récente, effectuée dans le bassin versant de la rivière Noire dans le piémont appalachien où l'infiltration a été simulée par le modèle de bilan hydrique en zone non saturée Agri Flux, a révélé que 74 % de l'infiltration se produit au moment de la fonte printanière (Laroque et Pharand, 2010). Les précipitations qui tombent sous forme de pluies en hiver provoquent des crues hivernales à l'origine de dégâts matériels parfois importants (p. ex. Groleau *et al.*, 2007). Du point de vue écologique, les débits hivernaux, qui proviennent principalement de l'eau de fonte de neige infiltrée au printemps et des pluies hivernales, déterminent le volume d'habitat disponible pour de nombreux organismes aquatiques et, de ce fait, influencent leur cycle de vie (p. ex. Belzile *et al.*, 1997; Cunjak *et al.*, 1998; Frenette *et al.*, 2008). Dans la rivière Catamaran, située au Nouveau-Brunswick (Canada) et caractérisée par un régime hydrologique de type nival comme celui observé au Québec, Cunjak *et al.* (1998) ont mis en évidence une relation entre les débits hivernaux et la survie des œufs de saumon.

Ainsi, l'abondance des juvéniles en été était grande après les hivers caractérisés par des débits élevés. Sur le plan socio-économique, les températures froides et la neige ont permis le développement des industries récréotouristiques nombreuses et diversifiées qui génèrent annuellement des milliards de dollars en retombées économiques au Québec.

1.2 Problématique, objectifs et hypothèses du travail

En raison du réchauffement climatique observé depuis la décennie 1970 (p. ex. Zhang *et al.*, 2000; Yagouti *et al.*, 2008), l'état physique des précipitations hivernales changera significativement. En effet, selon les différents modèles climatiques, les précipitations hivernales seront les plus affectées en raison de leur sensibilité à la hausse de la température de l'air (p. ex. Boyer *et al.*, 2010; Yagouti *et al.*, 2008). Ces modèles climatiques prédisent ainsi une diminution significative des précipitations sous forme de neige, mais une hausse importante de celles qui tombent sous forme de pluies. Ce changement de l'état physique des précipitations modifiera plus ou moins profondément le cycle hydrologique naturel des cours d'eau (hausse des débits en hiver) et leur évolution morphologique (hausse du charriage et exacerbation de l'érosion des lits et des berges), le cycle de vie des organismes aquatiques dans sa phase hivernale ainsi que toutes les activités socio-économiques qui dépendent à des degrés divers de la quantité de neige.

Cependant, malgré l'importance climatique, hydrologique, écologique et socio-économique des précipitations hivernales au Québec, il existe encore très peu d'études sur leur variabilité spatio-temporelle en relation avec la hausse de la température observée depuis la décennie 1970 au Québec (Yagouti *et al.*, 2008). Groleau *et al.* (2007) ont analysé la variabilité spatio-temporelle de la quantité de pluie qui tombe en janvier et en février pendant la période 1960-2005 au moyen de la méthode de Mann-Kendall. Yagouti *et al.* (2008) ont analysé la variabilité spatio-temporelle de la quantité de neige de janvier à mars au moyen de la méthode de régression linéaire. Enfin, Brown (2010) a analysé la variabilité spatio-temporelle de la couverture nivale au Québec au moyen de la méthode de Mann-Kendal. Il s'ensuit que ces études n'ont pas comparé la variabilité spatio-temporelle de la quantité de neige et celle de pluies afin de pouvoir déterminer si la diminution de la neige se fait aux dépens de celle de la pluie. De plus, ces études n'ont pas analysé conjointement la variabilité spatio-temporelle de la température et des précipitations afin de déterminer s'il existe une relation statistique significative entre les deux variables en hiver. Enfin, aucune de ces études ne s'est intéressée à l'analyse de la relation entre les précipitations, la température et les indices climatiques au Québec en hiver. Toutefois, ce lien a été analysé dans un cadre régional (Shabbar *et al.*, 1997; Kingston *et al.*, 2006). Il ressort de ces études que les précipitations et les températures hivernales dans la partie orientale du Canada (incluant le Québec) sont corrélées négativement aux oscillations suivantes : Oscillation Nord Atlantique (ONA), Oscillation Arctique (OA) et Oscillation Australe (OAU). Toutefois, ces dernières études n'ont analysé que quelques stations au Québec. Un tel échantillon ne permet pas de dresser un portait global de la relation entre les indices climatiques et les éléments climatiques en hiver.

Par ailleurs, dans une étude récente relative à la variation interannuelle des débits saisonniers hivernaux, Assani *et al.* (2012) ont mis en évidence trois régions hydrologiques homogènes : une en rive nord et deux autres en rive sud de part et d'autre du 47 °N. En rive nord, les débits hivernaux ont significativement augmenté dans le temps depuis 1950, mais ils ont diminué en rive sud au sud du 47 °N. Au nord de ce parallèle, aucun changement ne fut observé. De plus, ces auteurs ont démontré une corrélation négative entre ces débits saisonniers et l'Oscillation Atlantique Multi-décennale (OAM) en rive sud du 47 °N, mais positive avec ONA en rive nord. Aucun lien significatif n'a été observé en rive sud au nord du 47 °N.

À la lumière de ces considérations, notre projet de recherche poursuit les deux principaux objectifs suivants :

1) Comparer la variabilité interannuelle de la température et des précipitations en hiver au Québec. Cet objectif repose sur l'hypothèse suivante : en raison de la hausse de la température, la quantité de précipitations sous forme liquide (pluies) a significativement augmenté au détriment de celle de la neige.

2) Il existe un lien entre les indices climatiques et les deux éléments climatiques (précipitations et température) en hiver au Québec. L'hypothèse qui sous-tend cet objectif est la suivante : les précipitations et les températures hivernales sont corrélées négativement aux indices ONA et OAU.

1.3 Méthodologie de recherche

1.3.1 Choix des stations à analyser et source des données climatiques

La mesure des précipitations et de la température en hiver a toujours constitué un défi important en climatologie en raison de la difficulté de mettre en opération les appareils de mesure et le manque d'accessibilité aux sites de mesure. Ainsi, la qualité de mesure de données est relativement faible comparée à celle effectuée pendant la période chaude. Ces difficultés affectent beaucoup plus les mesures de précipitations que celles de la température. Il en résulte souvent des lacunes de données dans de nombreuses séries de mesure. Outre ces difficultés d'ordre technique, la rationalisation des réseaux de mesures de données hydroclimatiques décrétée par le gouvernement fédéral du Canada durant la décennie 1980 (voir Ouarda *et al.*, 1999) a provoqué l'interruption des mesures de données dans de nombreuses stations. En tenant compte de ces différentes difficultés, on a retenu 17 stations de mesures des températures et des précipitations réparties de manière assez régulière dans le territoire de la Province du Québec. Ces 17 stations ont été groupées dans trois régions hydroclimatiques définies par Assani *et al.* (2012). Notons toutefois qu'après l'an 2000, comme on l'a déjà mentionné, la rationalisation des stations de mesure a provoqué une interruption de mesure dans de nombreuses stations parmi les 17 stations retenues. En raison de cette interruption, pendant la période 1950-2010, on a analysé seulement 7 stations qui avaient des données de mesure quasi complètes.

En ce qui concerne les indices climatiques, on a retenu six indices dont l'influence sur la variabilité spatio-temporelle des variables hydroclimatiques (températures, précipitations et débits) a été déjà démontrée en Amérique du Nord, en général, au

Québec, en particulier (p. ex. Anctil and Coulibaly, 2004; Assani *et al.*, 2010a, 2010b; 2011; Coulibaly and Burn, 2005; Curtis, 2008; Déry and Wood, 2004, 2005; Enfield *et al.*, 2001; McCabe *et al.*, 2004). Pour chaque indice et à chaque année, on calculera des moyennes saisonnières hivernales (de décembre à mars) et automnales (d'août à novembre).

1.3.2 Analyse statistique

1.3.2.1 Constitution des séries statistiques climatiques

Pour chaque station, on a constitué deux séries statistiques de température et deux séries statistiques de précipitation;

- la série des températures moyennes maximales journalières (Tmax) constituée des moyennes maximums journalières mesurées de décembre à mars chaque année;
- la série des températures moyennes minimales journalières (Tmin) constituée des moyennes minimales journalières mesurées de décembre à mars chaque année;
- la série des totaux de pluies constituée par la somme des quantités journalières de pluies mesurées de décembre à mars chaque année;
- la série des totaux journaliers de neige constituée par la somme des hauteurs de neige mesurées de décembre à mars chaque année.

1.3.2.2 Analyse de la variabilité interannuelle des températures et des précipitations

L'analyse de la variabilité interannuelle a été effectuée en deux étapes.

Pour vérifier si la moyenne de la série hydrologique a significativement changé dans le temps, on a appliqué la méthode de Lombard. Le choix de cette méthode s'explique par le fait qu'elle permet de déterminer la nature abrupte ou progressive du changement de la moyenne ou de la variance. Ainsi, cette méthode détermine de manière rigoureuse les dates de changement des moyennes et des variances des séries climatiques analysées. Cette méthode a été décrite notamment par Lombard (1987) et ses applications en hydrologie et en géomorphologie peuvent être lues dans Assani *et al.* (2011) ainsi que Quessy *et al.* (2011).

À la seconde étape, on a analysé la dépendance entre les séries de température et celle des précipitations à chaque station au moyen de la méthode de copules.

1.3.2.3 Analyse de la relation entre les indices climatiques et les variables climatiques

Afin de déterminer l'indice climatique qui influence la variabilité spatio-temporelle de la température et des précipitations (pluie et neige), on a effectué une analyse de corrélation canonique, qui englobe à la fois l'analyse de régression multiple et celle en composantes principales et permet de définir les liens entre les deux groupes de variables climatiques.

À la dernière étape, on a appliqué la méthode de copules pour analyser le changement du lien de dépendance qui peut survenir dans le temps entre les indices climatiques et les variables climatiques.

1.4 Résultats de recherche

1.4.1 Détection des ruptures des moyennes de la température et des précipitations en hiver au Québec méridional

L'analyse de la variabilité interannuelle de la température et des précipitations (pluie et neige) en hiver au Québec méridional, au moyen de la méthode de Lombard, montre que :

Pendant la période 1950-2000, en ce qui concerne la température extrême maximale, trois stations ont connu une seule rupture de leurs moyennes (Natashquan, Sainte-Rose et Shawville). En ce qui concerne la température minimale, la même tendance est observée pour les stations Natashquan et Sainte-Rose. Outre ces deux stations, la station de Coaticook a connu une rupture de la moyenne survenue plutôt au début de la décennie 1980. Ces changements se traduisent par une diminution significative des moyennes des séries climatiques pour les deux stations situées au nord de 47 °N (Natashquan et Sainte-Rose), mais une augmentation significative de la température dans les stations situées au sud du 47 °N (Shawville et Coaticook).

Quant aux pluies, seule la station de Bagotville a connu une rupture de la moyenne survenue au début de la décennie 1970. Après cette rupture, la quantité de pluies a significativement augmenté.

En revanche, 7 stations ont connu une rupture de la moyenne des accumulations totales de la neige en hiver. Cette diminution a particulièrement affecté les stations situées dans la région hydroclimatique sud-ouest en rive nord du fleuve et jouissant d'un climat de type continental.

Pendant la période 1950-2010, on observe des ruptures de moyennes aux stations qui n'en ont pas connu pendant la période 1950-2000. En ce qui concerne la température, il s'agit des stations de Montréal St-Alban et de Saint-Michel. Quant aux précipitations, une rupture de la moyenne de la quantité totale des pluies a été observée à une seconde station, en l'occurrence la station de Saint-Malo. La rupture des moyennes des accumulations totales de neige ainsi que leurs dates d'occurrence et leur nature abrupte sont observées aux mêmes stations que pendant la période 1950-2000.

1.4.2 Détection de changement de degré de dépendance entre la température et les précipitations

Pendant la période 1950-2000, les changements de dépendance entre la température maximale et les précipitations ont été observés seulement à deux stations :

la station de Sept-Îles (pour la neige) et celle de Coaticook (pour les pluies). Quant aux températures extrêmes minimales, les changements de dépendance ont été observés à cinq stations. Ils ne concernent qu'exclusivement la dépendance entre la température maximale et la quantité de neige. Aucun changement de la dépendance n'a été observé entre la température extrême minimale et la quantité totale de pluies.

Pendant la période 1950-2010, aucun changement de dépendance ne fut observé même pour les stations qui ont connu des ruptures des moyennes des températures et des précipitations.

1.4.3 Relation entre les indices climatiques et les variables climatiques

Les résultats obtenus par les indices automnaux et hivernaux trimestriels sont similaires à ceux des indices automnaux et hivernaux calculés sur quatre mois.

Les valeurs des coefficients canoniques de corrélation (r) calculées avec les indices hivernaux sont globalement plus élevées que celles calculées avec les indices automnaux dans les trois régions hydroclimatiques. Il s'ensuit que les indices hivernaux sont mieux corrélés aux quatre variables climatiques que les indices automnaux. De plus, les indices climatiques hivernaux ont produit un nombre d'axes canoniques statistiquement significatifs plus élevé que les indices automnaux dans les trois régions hydroclimatiques. En ce qui concerne les liens entre les variables climatiques et les indices climatiques, les deux types d'indices saisonniers conduisent aux mêmes résultats. C'est la raison pour laquelle nous allons interpréter seulement les résultats obtenus avec les indices climatiques hivernaux afin de limiter la redondance des résultats.

En tenant compte de la significativité statistique des axes canoniques, en ce qui concerne les coefficients de structure calculés au moyen des indices climatiques hivernaux, dans la région est, la température extrême maximale et minimale en hiver est corrélée positivement à l'indice hivernal AMO, et dans une moindre mesure, négativement à AO. Les précipitations (pluie et neige) sont corrélées négativement à PDO. Dans la région sud-est, les précipitations liquides (pluies) sont corrélées positivement à AO alors que les précipitations solides (neige) sont corrélées négativement à PDO. Dans la région sud-ouest, la quantité de la neige est fortement corrélée négativement à PDO et la température minimale l'est à AO.

L'analyse de l'évolution du lien de dépendance entre les indices climatiques et les variables climatiques montre que dans la région est, les changements du lien de dépendance ont été observés dans deux stations. Il s'agit des stations de Bagotville (le lien entre PDO et SNT) et de Mont-Joli (le lien entre AMO et Tmin). Dans la région sud-est, ce changement a été observé à la station de Saint-Malo (AO et RNT). Enfin, dans la région sud-ouest, aucun changement de dépendance entre les indices climatiques et les variables climatiques n'a été observé.

CHAPITRE II

COMPARISON OF THE TEMPORAL VARIABILITY OF WINTER DAILY EXTREME TEMPERATURES AND PRECIPITATIONS IN SOUTHERN QUEBEC (CANADA) USING THE LOMBARD AND COPULA METHODS

Ce chapitre est présenté sous forme d'article, en anglais, et a été soumis dans la revue *International journal of climatology* (Nadjet **Guerfi**, Ali A. **Assani**, Mhamed **Mesfioui,** Christophe **Kinnard**) sous le titre : « Comparison of the temporal variability of winter daily extreme temperatures and precipitations in southern Quebec (Canada) using the Lombard and copula methods ».

Comparison of the temporal variability of winter daily extreme temperatures and precipitations in southern Quebec (Canada) using the Lombard and copula methods

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Abstract

Although numerous studies have looked at the long-term trend of the temporal variability of winter temperature and precipitation in southern Quebec, no study has focused on the shifts in series means and the dependence between these two types of climate variables associated with this long-term trend. To fill these gaps, we applied the Lombard method to detect the shifts in mean values and the copula method to detect any change in dependence between extreme (maximum and minimum) temperatures and precipitation (snow and rain) over the periods from 1950 to 2000 (17 stations) and from 1950 to 2010 (7 stations). During these two periods, the shifts in mean values of temperature and precipitation were recorded at less than half of the stations. The only significant change observed at the provincial scale is a decrease in the amount of snow, which occurred in many cases during the 1970's. This decrease affected stations on the north shore (continental temperate climate) more strongly than stations on the south shore (maritime temperate climate) of the St. Lawrence River. However, this decrease in amount of snow had no impact on the dependence over time between temperature and precipitation as snow.

Keywords: winter maximum and minimum daily temperature, winter rainfall, winter snowfall, Lombard method, copula, southern Quebec

Introduction

In the current climate change context, an increasing amount of work focuses on changes that affect the temporal variability of temperature and precipitation in many regions of the world. Many studies have looked at this issue in Canada in general and in Quebec in particular (e.g., Adamowski *et al.*, 2013; Brown and Braaten, 1998; Brown and Goodison, 1966; Fortin and Hétu, 2013; Groisman *et al.*, 1994; Langlois *et al.*, 2004; Mekis and Vincent, 2011; Nalley *et al.*, 2012; Stuart and Isaac, 1999; Turner and Gyakum, 2010; Vincent and Mékis, 2006; Yagouti *et al.*, 2008; *Zeng et al.*, 2011; Zhang *et al.*, 2000). These studies have shown that the extent of changes in temperature and precipitation regimes is geographically and seasonally dependent. Based on an analysis of trends in temperature and precipitation from 1900 to 1998, Zhang *et al.* (2000) observed a generalized increase in annual mean temperature ranging from 0.5 to 1.5°C in southern Canada, particularly in the western part of the country. This warming, however, is greater for minimum temperatures than for maximum temperatures. At the seasonal scale, warming is generalized in winter and spring, with the most extensive warming having occurred in the spring. However, data from 1950 to 1998 revealed a decrease in temperature in the northeastern part of Canada, including Quebec. As far as precipitation is concerned, Zhang *et al.* (2000) noted a generalized increase in total annual precipitation ranging from 5 to 35% from 1900 to 1998 in southern Canada. This increase is thought to result mainly from increased amounts of snow in fall and winter, with the snow to total precipitation ratio having increased significantly in many regions of the country. However, negative trends of this ratio were observed in other southern regions in winter. In southern Quebec, no significant change in the amount of precipitation is observed either for winter or spring.

These trends in temperature and precipitation were for the most part confirmed by subsequent studies in various regions of Canada. However, the extent of temperature and precipitation increases varies from one study to the next due to differences in the period over which data are analyzed. For Quebec, Yagouti *et al.* (2008) also observed a trend of increasing temperature from 1960 to 2005, particularly in the southern, western and central regions of the province. This warming trend is particularly strong in winter. The same authors also observed a trend of increasing annual total precipitation, as well as of low intensity rain in winter. In contrast, total snow height decreased, a trend also observed by Brown (2010). For their part, Fortin and Hétu (2013) did not detect a generalized trend of increasing temperature or precipitation in the Chic-Choc Mountains region of the Gaspé Peninsula, in eastern Quebec.

However, all these studies were limited to an analysis of the long-term trend of these climate variables using the Mann-Kendall method, a method which has the following two drawbacks:

1. It cannot not establish whether such long-term trends are related to one or to multiple shifts in mean values of climate series. This is a key question because, unlike the long-term trend, the timing of the shifts in mean values can be used to determine more or less precisely the factors that cause changes in the stationarity of hydroclimatic time series (e.g., Assani *et al.*, 2014).

2. It cannot determine the extent of change affecting the mean or variance of a climate data series because changes in temperature or precipitation do not lead to regular and constant increases or decreases of these values over time.

3. Changes in dependence between two variables over time cannot be constrained using this method. As climate warms, the notion that increasing winter temperature will result in increasing amounts of rain associated with a concomitant decrease in amounts of snow is gaining acceptance. For southern Quebec, this hypothesis is supported by climate model predictions (Boyer *et al.*, 2010). Although the Mann-Kendall method has been used to show that winter temperatures in Quebec are rising (e.g., Yagouti *et al.,* 2008), the impact of this warming on the dependence between temperature and precipitation has never been studied.

The two goals of this study are therefore as follows:

- To determine, using the Lombard method (Lombard, 1987; Quessy *et al.*, 2011), whether the long-term trends of temperature and precipitation in southern Quebec are linked to shifts in mean values of these series.

- To determine, using the copula approach, if the dependence between winter temperature and precipitation type in southern Quebec changes over time.

Methods

Choice and selection of stations

To analyze the largest possible number of stations, the study was restricted to the period from 1950 to 2010. Very view measurements of climate variables at a large number of stations are available prior to 1950. However, after 2000, climate variable measurements stopped at many stations, likely as a result of funding cuts resulting from program revision by the Government of Canada during the 1990's (Pilon *et al.*, 1996). Given this shift, the analysis was carried out in two steps. First, we analyzed the temporal variability of climate variables from 1950 to 2000. To this end, all stations for which temperature and precipitation were measured over at least 40 years were selected, which yielded 17 stations spread out nearly evenly throughout the southern part of the Province of Quebec (Figure 1 and Table 1). These stations cover the three homogeneous hydroclimate regions identified in southern Quebec (e.g., Assani *et al.*, 2011), namely the southeast hydroclimate region (SE) located south of 47°N on the south shore (right bank) of the St. Lawrence River; the eastern hydroclimate region (E), located north of 47°N; and the southwest hydroclimate region (SW), primarily located on the north shore (left bank) of the river. The second step consisted in analyzing the temporal variability of climate variables over the period from 1950 to 2000. Because data measurements ceased at many stations after 2000, only 7 stations were selected for this step.

Temperature and precipitation (rain and snow) data were taken from the Environment Canada web site (http://www.climate.weatheroffice.ec.gc.ca/, viewed in March 2011). These data are from Environment Canada's Canadian Daily Rehabilitated Database (Mekis and Hogg, 1999; Vincent and Gullet, 1999; Vincent and Zhang, 2002). While the quality of these winter data is generally good, there are shifts in data continuity at some stations (Kingston *et al.*, 2006).

Temperature and precipitations series

Two temperature series were assembled, namely a daily extreme maximum and a daily extreme minimum temperature series. These two series consist respectively of mean values of daily maximum (Tmax) and minimum (Tmin) temperatures measured from December to March during the period from 1950 to 2000 (17 stations) and from 1950 to 2010 (7 stations). Two precipitation series were also assembled: a rainfall series and a snowfall series. Both series comprise the total daily sum, respectively, of rainfall (RT) and snowfall (ST) measured from December to March from 1950 to 2000 (17 stations) and from 1950 to 2010 (7 stations). Because no snow water equivalent data are available, all previous studies were restricted to analyzing the amount of snow. A separate analysis of the amount of rain and snow will make it possible to test whether, along with increasing winter temperature, the amount of rain has increased significantly in winter at the expense of the amount of snow. It should be mentioned that, in southern Quebec, depending on the region, winter starts in December and ends in March.

Statistical analysis

The goals of the statistical analysis are two-fold:

- To detect the shifts in mean values of climate data series using the Lombard method.
- To detect any change in the relationship (dependence) over time between temperature and precipitation using the copula method.

Lombard method

Whether in climatology (see reviews by Lund *et al.*, 2007 and Reeves *et al.*, 2007) or in hydrology (see review by Kundzewicz and Robson, 2004), many methods have been proposed to detect shifts in mean values of hydroclimate data series. However, as pointed out by Villarini *et al.* (2011), all these tests can detect abrupt shifts, but not gradual ones, which may be more frequent in hydroclimate data series. The only test that can detect both types of shifts is the Lombard method (Lombard, 1987). According to

Quessy *et al.* (2011), this method is a powerful statistical test able to detect very small changes in mean values, and has a high potential for applications in the environmental sciences. For these reasons, we selected the Lombard method to detect potential abrupt and gradual shifts. Suppose a series of observations, noted $X_1,\ldots,X_n$, where X_i is the observation taken at time $T = i$. These observations are supposed to be independent. One question of interest is to see whether the mean of this series has changed. If μ_i refers to the theoretical mean of X_i, then a possible pattern for the mean is given by Lombard's smooth-change model, where

$$\mu_i = \begin{cases} \theta_1 & \text{if } 1 \le i \le T_1 \\ \theta_1 + \dfrac{(i - T_1)(\theta_2 - \theta_1)}{T_2 - T_1} & \text{if } T_1 < i \le T_2 \\ \theta_2 & \text{if } T_2 < i \le n \end{cases} \qquad (1)$$

In other words, the mean changes gradually from θ_1 to θ_2 between times T_1 and T_2. As a special case, one has the usual abrupt-change model when $T_2 = T_1 + 1$. In order to test formally whether the mean in a series is stable or rather follows model (1), one can use the statistical procedure introduced by Lombard (1987). To this end, define R_i as the rank of X_i among $X_1, \ldots X_n$. Introduce the Wilcoxon score function $\phi(u) = 2u - 1$ and define the rank score of X_i by

$$Z_i = \frac{1}{\sigma_\phi}\left\{\phi\left(\frac{R_i}{n+1}\right) - \bar{\phi}\right\}, \qquad i \in \{1,\ldots,n\} \qquad (2)$$

where

$$\bar{\phi} = \frac{1}{n}\sum_{i=1}^{n} \phi\left(\frac{i}{n+1}\right) \quad \text{and} \quad \sigma_\phi^2 = \frac{1}{n}\sum_{i=1}^{n}\left\{\phi\frac{i}{n+1} - \bar{\phi}\right\}^2 \qquad (3)$$

Lombard's test statistic is

$$S_n = \frac{1}{n^5} \sum_{T_1=1}^{n-1} \sum_{T_2=T_1+1}^{n} L_{T_1 T_2}^2 \tag{4}$$

where

$$L_{T_1 T_2} = \sum_{j=T_1+1}^{T_2} \sum_{i=1}^{j} Z_i \tag{5}$$

At the 95% confidence interval, one concludes that the mean of the series changes significantly according to a pattern of type (1) whenever $S_n > 0.0403$. This value correspond to the theoretical (critical) values (see Lombard, 1987) defining the significance level at 5% for the test. Note that the equation proposed by Lombard (1987) to detect multiple abrupt changes in the mean of a statistical series was also applied. This formula confirmed results obtained using equation 1. It is important to note that the assumptions regarding Lombard method (see Lombard, 1987; Quessy *et al.*, 2011) are valid for this application. Among these hypotheses, we checked for autocorrelation between values in analyzed hydrological series. Statistically significant autocorrelation was removed by using the pre-whitening procedure (Von-Storch and Navarra, 1995). Finally, the Lombard method can be applied even if data are missing in a climate series.

Copula method

The dependence relationship between two climate variables may change over time for a variety of reasons. It is therefore important to detect this type of change in order to interpret more accurately the evolution of climate in a given region. The only method that can detect changes in dependence between two climate variables is the copula method. The dependence in a random vector (*X, Y*) is contained in its corresponding copula function C. Specifically, the celebrated theorem of Sklar (1959) ensures that there exists a unique $C : [0, 1]^2 \longrightarrow [0, 1]$ such that

$$P(X \leq x, Y \leq y) = C\{P(X \leq x), P(Y \leq y)\}. \tag{6}$$

Quessy *et al.* (2012) developed a testing procedure to identify a change in the copula (*i.e.* dependence structure) of a bivariate series $(X_1, Y_1), \ldots, (X_n, Y_n)$. The idea is based on Kendall's tau, which is a nonparametric measure of dependence. Let $\hat{T}_{1:T}$ be Kendall's tau measured for the first T observations and $\hat{T}_{T+1:n}$ be Kendall's tau for the remaining $n-T$ observations. The proposed test statistic is

$$M_n = \max_{1<T<n} \frac{T(n-t)}{n\sqrt{n}} \left| \hat{T}_{1:T} - \hat{T}_{T+1:n} \right| \tag{7}$$

i.e. a maximum weighted difference between the Kendall's tau. Since M_n depends on the unknown distribution of the observations, the so-called multiplier re-sampling method is used for the computation of p-values. Specifically, for n sufficiently large (n> 50), this method yields independent copies $M_n^{(1)}, \ldots M_n^{(N)}$ of M_n. Then, a valid p-value for the test is given by the proportion of $M_n^{(i)}$'s larger than M_n. For more details, see Quessy *et al.* (2012). Usually, one can expect that the series $X_1, \ldots, X_n$ and $Y_1, \ldots, Y_n$ are subject to changes in the mean and / or variance following, e.g. the smooth-change model (Lombard, 1987). If such changes are detected, the series must be stabilized in order to have (approximately) constant means and variances. Finally, a change in the degree of dependence between two series is statistically significant when M_n > Vc, where Vc is the critical value derived from observational data.

In the present study, the copula method was used to analyze changes in dependence between daily extreme (maximum and minimum) temperatures and rainfall on one hand, and these same temperatures and snowfall, on the other hand. Any statistically significant shift in mean values was removed prior to applying this method.

Results

The shifts in mean values of winter temperature and precipitation in southern Quebec

Results obtained using the Lombard method are shown in Tables 2 and 3. Three stations record a single shift in the mean values of winter daily mean maximum temperature (Tmax) over the period from 1950 to 2000. These shifts took place during the beginning of the 1970's, except at the Shawville station, where it occurred in 1982. The same trend is observed for winter daily mean minimum temperature (Tmin) for the Natashquan and Sainte-Rose stations. For Coaticook station, the shift took place in 1980. For both maximum and minimum temperatures, all shifts in mean values of the temperature series are abrupt. These shifts mark a significant decrease in mean values for the two stations located north of 47°N (Figures 2 and 3), but a significant increase in temperature at stations located south of 47°N (Figures 4 and 5). As far as rain is concerned, Bagotville is the only station where a shift in mean values is recorded, in the early 1970's, after which the amount of rain increased significantly (Figure 6). In contrast, a shift in mean values of total snowfall in winter is recorded at seven stations. After this abrupt change, total snowfall mean values decrease significantly (Figure 7), particularly at stations located in the southwest hydroclimate region, on the north shore of the St. Lawrence River, characterized by a continental climate. Unlike for temperature, however, this shift occurred in the late 1970's in many cases. In addition, only one (Sainte-Rose) of the seven stations recorded shift in both mean temperature and mean total snowfall.

Over the period from 1950 to 2010 (Table 3), the shifts in mean values are observed at stations that did not show shifts for the period from 1950 to 2000. This is the case for temperature at the Montreal, Saint-Alban and Saint-Michel stations. These shifts in mean occurred during the 1990's, except for daily mean maximum temperature at the last station. For precipitation, a shift in mean values of the total amount of rain was recorded at a second station, the Saint-Malo station, and this shift took place in the 1960's. The shift in mean values of total snow accumulation, and their dates of occurrence and abrupt change are observed at the same stations as for the period from 1950 to 2000.

Changes in dependence between temperature and precipitation

Tables 4 and 5 show copula results derived between extreme temperature and precipitation for the period from 1950 to 2000. Changes in dependence between maximum temperature and precipitation (Table 4) are recorded at only two stations, Sept-Îles (for snowfall) and Coaticook (for rainfall). Changes in dependence between these two variables took place in the early 1970's at both stations (Figure 8). In contrast, changes in the dependence between minimum extreme temperature and precipitation were observed at five stations (Figure 9), and only affect the dependence between minimum temperature and amount of snow. These changes took place during the 1970's for the Sept-Îles and Ste-Rose stations, during the 1960's for the Trois-Pistoles, Shawville and the Matawin station. No change in the dependence between minimum extreme temperature and total amount of rain is recorded. No change in dependence was recorded for the period from 1950 to 2010, even at stations where shifts in mean values of temperature and precipitation are observed.

Discussion and conclusion

Several studies have shown that the temporal variability of temperature at many stations in southern Quebec is characterized by a significant positive long-term trend (e.g., Yagouti *et al.*, 2008; Vincent and Mekis, 2006; Zhang *et al.*, 2000). In general, however, this warming, which is estimated at 0.2°C-0.4°C per decade in southern Quebec (Ouranos, 2010), affects daily minimum temperatures much more strongly than it does maximum temperatures. For precipitation, previous work highlighted a significant decrease in the amount of snow over time in southern Quebec (e.g., Brown, 2010; Zhang *et al.*, 2000).

None of these studies, however, has shown that these changes in the long-term trend of temperature or amount of snow induced the shifts in mean values of climate series and/or affected the dependence between winter temperature and precipitation over time in southern Quebec. To do this, we applied the Lombard method to detect the shifts in mean values and the copula method to detect changes in dependence between climate variables.

Analysis of 17 weather stations over the period from 1950 to 2000 revealed the shifts in mean values of maximum and minimum extreme temperatures at 3 stations. The analysis also yielded the shifts in mean values of total rainfall (1 station) and snowfall (7 stations). Analysis of 7 stations for the 1950-2010 period revealed the shifts in mean values of maximum and minimum extreme temperatures at 3 and 1 stations, respectively, as well as the shifts in mean values of total rainfall and total snowfall for 2 and 3 stations, respectively.

The shifts in mean temperature values reflect a significant increase in mean values of the time series for stations located south of 47°N, but a significant decrease in mean values for stations located north of 47°N. For observed precipitation, the shifts reflect a significant increase in the amount of rain, but a decrease in amount of snow. These results do not confirm results for the long-term trend: while the change in long-term trend appears to affect all of southern Quebec (Ouranos, 2010), the shifts in mean values affect a very small number of stations. In fact, for the period from 1950 to 2000, less than 20% of analyzed stations record a shift in mean values of temperature and amount of rain and 40% of stations record a shift in mean values of the amount of snowfall.

The shifts in mean values for all four climate variables over the period from 1950 to 2000 occurred in many cases in the early 1970's, a decade for which many shifts in hydoclimatic data series are observed worldwide (e.g. Ivanov and Evtimov, 2010; Pillai and Mohankumar, 2010; Trenberth and Hurell, 1994; Wang *et al.*, 2010). In Quebec, for instance, Perrault *et al.* (1999) observed the shifts in mean values of annual rainfall in the eastern parts of Canada (including southern Quebec) and the United States. While the causes of these shifts remain unclear, two hypotheses are often suggested: 1) climate warming resulting from increased anthropogenic greenhouse gases (e.g., Klein-Tank *et al.*, 2005); and 2) changes in overall the atmospheric circulation. For instance, according to Wang *et al.* (2010), "in the mid-1970's, the atmospheric circulation underwent significant changes in many regions of the world". This change in general atmospheric circulation affected the variability of climate indices and of hydroclimatic variables (temperature, precipitation, wind, streamflow, etc.). Data are not available to discriminate between these hypotheses as part of the present study, but irrespective of their cause, the shits in mean values of hydroclimatic series observed during the 1970's appear to follow a global rather than local pattern.

Although the shifts in mean values of temperature and precipitation series are recorded at several stations, few changes in the dependence between these two climate variables are observed. Over the period from 1950 to 2010, no change in dependence is observed, and for the 1950-2000 period, such changes mainly relate to the amount of snowfall and minimum temperatures. Consequently, contrary to a common assumption, changes in maximum or minimum temperature do not necessarily affect the amount of snow or rain. In the case of Quebec, a decrease in amount of snow cannot be linked to a significant increase in temperature. Other factors (convective movements, available moisture, cloud-forming processes, etc.) may have a significant influence on the amount of precipitation in a given region.

Finally, in this study, we highlighted the influence of the length of the period analyzed on the detection of shifts in mean values and the dependence between climate variables. Thus, at some stations, shifts in mean values were detected during the period from 1950 to 2000, but not during the period from 1950 to 2010, or vice versa. Many authors have noted this influence of the length of the period analyzed in the past (e.g., Ouarda *et al.*, 1999; Zhang *et al.*, 2000). According to Ouarda *et al.* (1999), a shift observed over a 40-year observation period may not be observable over 100 years since decadal scale fluctuations may be naturally present even though they remain unexplained. Aside from this, it is important to keep in mind that the largest changes may occur after the period that is being analyzed. In our study, changes that occurred at the end of the 1990's or after that decade would not have been detected in an analysis of data from 1950 to 2000. This is the case for the Montreal station, where the shift in mean values of maximum daily temperatures took place in the middle 1990's, and was, as a result, likely undetectable over the 1950-2000 analysis period because the increase in temperature was greater in the 2000 decade. From a statistical standpoint, adding or removing data in a climate series may lead to significant changes in the statistical properties of this series (moments of order: mean, variance, etc.). These changes may or may not result in the appearance of a shift in mean values of the series. Thus, Zhang *et al.* (2000) observed certain significant statistical trends in temperature and precipitation in Canada during the period from 1900 to 1998 which were not observable over the period from 1950 to 1998, and vice versa.

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Table 1. Climatic stations.

Code	Station	ID	Altitude (m)	Latitude (N)	Longitude (W)	Years
SE1 (1)	Coaticook	7021840	259	45°09’	71°48’	51
SE2 (2)	Granby	7022802	168	45°23’	72°42’	47
SE3 (3)	Magog	7024440	274	45°16’	72°07’	51
SE4 (4)	Montréal	7025250	36	45°28’	73°45’	51
SE5 (5)	Philipsburg	7026040	53	45°02’	73°05’	51
SE6 (6)	St Malo d’Auckland	7027520	564	45°12’	71°30’	51
E1 (7)	Bagotville	7060400	159	48°20’	71°00’	51
E2 (8)	Mont Joli A	7055120	48	48°36’	68°13’	51
E3 (9)	Natashquan A	7045410	575	48°57’	65°31’	51
E4 (10)	Sept Iles A	7047910	310	50°13’	66°16’	51
E5 (11)	Ste Rose du Degelis	7057720	151	47°34’	68°38’	50
E6 (12)	Trois-Pistoles	7058560	58	48°09’	69°07’	49
SW1 (13)	Chelsea	7031660	112	45°31’	75°47’	51
SW2 (14)	Nominingue	7035520	305	46°23’	75°03’	51
SW3 (15)	Shawville	7038040	168	45°37’	76°28’	40
SW4 (16)	St Alban	7016800	76	46°43’	72°05’	51
SW5 (17)	St-Michel-Des-Saints	7077570	350	46°41’	73°55’	43

Table 2. Sn values and dates of shifts in mean values calculated for the four climate variables (1950-2000) using the Lombard method.

Stations	Daily maximum temperature (Tmax)		Daily minimum temperature (Tmin)		Rainfall		Snowfall	
	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2
Southeast Hydroclimate Region								
Coaticook	0.0184	-	**0.0999**	**1978-1980**	0.0223	-	0.0150	-
Granby	0.022	-	0.0389	-	0.0129	-	0.0063	-
Magog	0.0314	-	0.0026	-	0.0106	-	**0.0529**	**1978-1979**
Montréal	0.0206	-	0.0061	-	0.0077	-	0.0375	-
Phillipsburg	0.0125	-	0.0089	-	0.0025	-	0.0034	-
Saint-Malo	0.0092	-	0.0064	-	0.0274	-	0.0247	-
Eastern Hydroclimate Region								
Bagotville	0.0089	-	0.0039	-	**0.0881**	1971-1972	0.0018	-
Mont Joli	0.0062	-	0.0255	-	0.0054	-	**0.0503**	**1978-1979**
Natashquan	**0.0556**	**1970-1971**	**0.0466**	**1970-1971**	0.0127	-	0.0282	-
Sept Îles	0.0321	-	0.0123	-	0.0111	-	0.0158	-
Sainte-Rose	**0.0590**	**1969-1970**	**0.0485**	**1971-1972**	0.0132	-	**0.0433**	**1969-1970**
Trois-Pistoles	0.0057	-	0.0052	-	0.0244	-	0.0015	-
Southwest Hydroclimate Region								
Chelsea	0.0213	-	0.0359	-	0.0061	-	**0.1183**	**1978-1979**
Nominingue	0.0080	-	0.0155	-	0.0033	-	**0.0528**	**1978-1979**
Saint-Alban	0.0068	-	0.0051	-	0.0112	-	**0.1214**	**1972-1973**
Saint-Michel	0.0399	-	0.0069	-	0.0034	-	**0.0605**	**1960-1961**
Shawville	**0.0408**	**1980-1982**	0.0087	-	0.0208	-	0.0015	-

Lombard test Sn values > 0.0403 are statistically significant at the 5% level. T1 and T2 are the years of start and end, respectively, of significant changes in mean values of a given series.

Table 3. Sn values and dates of shifts in mean values calculated for the four winter climate variables (1950-2010) using the Lombard method.

Stations	Daily maximum temperature (Tmax)		Daily minimum temperature (Tmin)		Rainfall		Snowfall	
	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2
				Southeast Hydroclimate Region				
Granby	0.0079	-	0.0326	-	0.0013	-	0.0344	-
Magog	0.0083	-	0.0024	-	0.0021	-	**0.0642**	**1978-1979**
Montréal	**0.0459**	**1994-1995**	0.0180	-	0.0119	-	0.0297	-
Saint-Malo	0.0380	-	0.0041	-	**0.0424**	**1965-1966**	0.0054	-
				Eastern Hydroclimate Region				
Bagotville	0,0389	-	0.0110	-	**0.0667**	**1971-1972**	0.0187	-
				Southwest Hydroclimate Region				
Saint-Alban	**0,0615**	**1996-1998**	**0.0641**	**1994-1995**	0,0055	-	**0.0756**	**1972-1973**
Saint-Michel	**0.0404**	**1971-1972**	0.0182	-	-	-	**0.0738**	**1976-1978**

Lombard test Sn values > 0.0403 are statistically significant at the 5% level. T1 and T2 are the years of start and end, respectively, of significant changes in mean values of a given series.

Table 4. Results of the analysis of the dependence between winter daily maximum temperatures (Tmax) and precipitation (rain and snow) (1950-2000).

Stations	Tmax and Snowfall			Tmax and Rainfall		
	Mn	V_C	p-value	Mn	V_C	p-value
Coaticook	0.3607	0.8439	0.7740	1.0356	0.8150	**0.0090**
Granby	0.4106	0.9227	0.7340	0.7302	0.8748	0.1340
Magog	0.5970	0.8598	0.2660	0.4147	0.8360	0.6640
Montréal	0.5004	0.8550	0.4460	0.5153	0.8297	0.4060
Phillipsburg	0.4971	0.9597	0.5350	0.9132	0.9027	0.0450
Saint-Malo	0.4746	0.8506	0.4660	0.5224	0.7841	0.3060
Bagotville	0.6052	0.9013	0.3380	0.3441	0.8041	0.7800
Mont Joli	0.5414	0.8456	0.4320	0.5253	1.0122	0.5780
Natashquan	0.4625	0.8932	0.5680	0.6658	0.8151	0.1450
Sept Îles	0.9146	0.8711	**0.0290**	0.6458	0.8164	0.1720
Sainte-Rose	0.7307	0.7586	0.0670	0.6010	0.8926	0.3020
Trois-Pistoles	0.7403	0.7437	0.0510	0.5734	0.8768	0.3040
Chelsea	0.8420	0.9062	0.0740	0.8342	0.9068	0.0750
Nominingue	0.5389	0.8276	0.3490	0.7130	0.8672	0.1680
Saint-Alban	0.5424	0.8672	0.3860	0.5768	0.8538	0.3270
Saint-Michel	0.7960	0.8636	0.0750	0.6572	0.9926	0.2980
Shawville	0.5400	0.7771	0.3050	0.6206	0.9236	0.2940

Statistically significant p-values are shown in bold.

Table 5. Results of the analysis of the dependence between winter daily minimum temperatures (Tmin) and precipitations (rain and snow) (1950-2000).

Stations	Tmin and Snowfall			Tmin and Rainfall		
	Mn	V_C	p-value	Mn	V_C	p-value
Coaticook	0.3877	0.8220	0.6940	0.8266	0.8950	0.0810
Granby	0.6331	0.9611	0.3220	0.7846	0.8660	0.1030
Magog	0.4262	0.8463	0.5920	0.5969	0.8313	0.2550
Montréal	0.5686	0.9209	0.3830	0.4610	0.8166	0.5090
Phillipsburg	0.7798	0.8932	0.1040	0.6448	0.8254	0.1780
Saint-Malo	0.4099	0.7648	0.5730	0.4982	0.8547	0.4180
Bagotville	0.7990	0.9208	0.1050	0.6025	0.9130	0.2710
Mont Joli	0.4539	0.8493	0.6360	0.4656	0.9753	0.6460
Natashquan	0.3816	0.8587	0.7850	0.7266	0.7700	0.0650
Sept Îles	0.8487	0.8282	**0.0400**	0.7298	0.8585	0.1240
Sainte-Rose	0.8570	0.7866	**0.0260**	0.4257	0.9183	0.7390
Trois-pistoles	0.9224	0.7159	**0.0100**	0.5535	0.8098	0.2840
Chelsea	0.8054	0.9124	0.1030	0.8685	0.9048	0.0730
Nominingue	0.7132	0.8977	0.1780	0.6837	0.8975	0.2290
Saint-Alban	0.5699	0.8259	0.3460	0.4466	0.7998	0.5190
Saint-Michel	0.9005	0.8650	**0.0390**	0.7118	0.9637	0.1890
Shawville	0.9224	0.7515	**0.0130**	0.8380	0.9108	0.0730

Statistically significant p values are shown in bold.

Table 6. Results of the analysis of the dependence between winter daily maximum temperatures (Tmax) and precipitations (rain and snow) (1950-2010).

Stations	Tmax and Snowfall			Tmax and Rainfall		
	Mn	V_C	p-value	Mn	V_C	p-value
Granby	0.5035	0.9363	0.5760	0.7405	0.9893	0.2070
Magog	0.5054	0.7815	0.3490	0.5024	0.8325	0.4290
Montréal	0.4506	0.8289	0.5340	0.6570	0.8837	0.2260
Saint-Malo	0.5335	0.8344	0.4180	0.5541	0.8337	0.3110
Bagotville	0.6479	0.9160	0.2680	0.6254	0.8585	0.2590
Saint-Alban	0.5233	0.8587	0.4130	0.7468	0.9934	0.2100
Saint-Michel	0.5954	0.8167	0.2460	0.6934	0.9828	0.2810

Statistically significant p-values are shown in bold.

Table 7. Results of the analysis of the dependence between winter daily minimum temperatures (Tmin) and precipitations (rain and snow) (1950-2010).

Stations	Tmin and Snowfall			Tmin and Rainfall		
	Mn	VC	p-value	Mn	VC	p-value
Granby	0.4827	0.9182	0.6040	0.8533	0.9231	0.0810
Magog	0.5161	0.8120	0.3690	0.5199	0.8062	0.3900
Montréal	0.5940	0.9076	0.2790	0.5037	0.8838	0.5100
Saint-Malo	0.5914	0.7732	0.2030	0.5149	0.8811	0.4710
Bagotville	0.6737	0.9044	0.2220	0.5349	0.8947	0.4820
Saint-Alban	0.4996	0.8861	0.4820	0.6240	0.9296	0.3180
Saint-Michel	0.7084	0.7596	0.0790	0.7171	0.9047	0.2030

Statistically significant p-values are shown in bold.

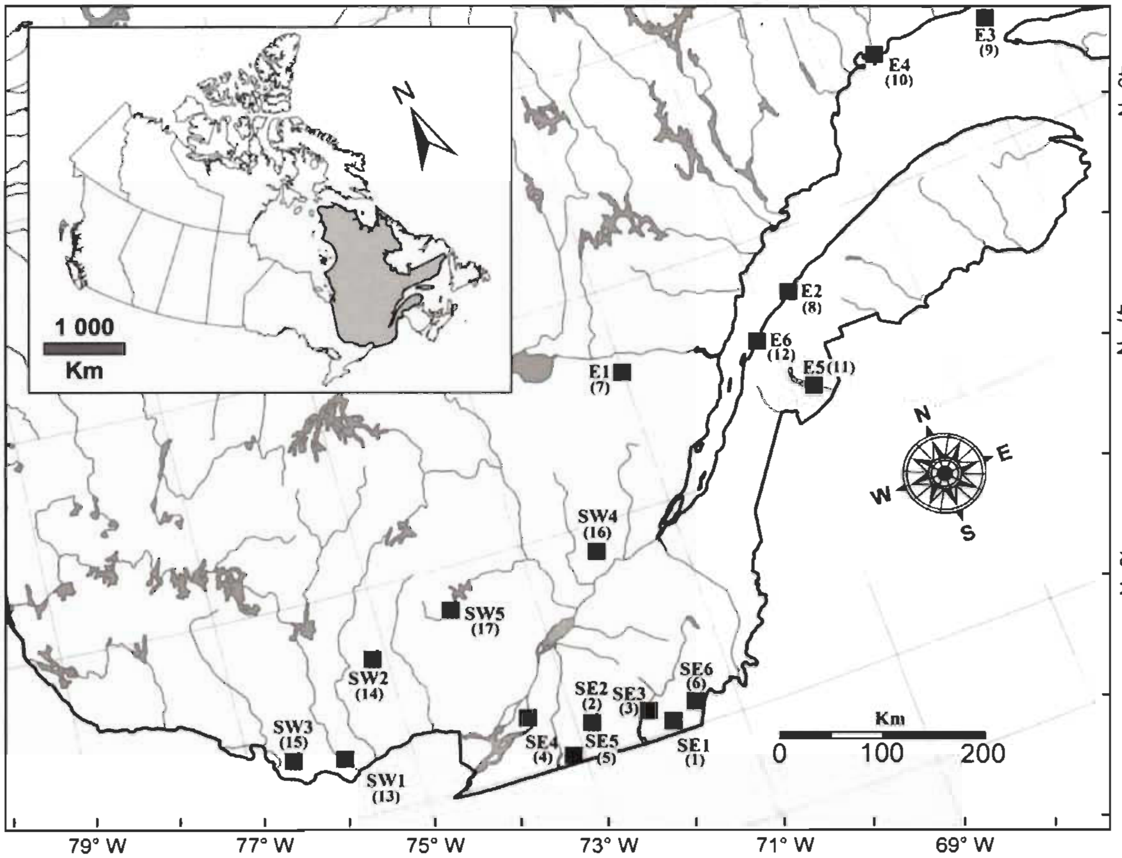

Figure 1. Location of stations. SE = Southeast Hydroclimate Region; E = Eastern hydroclimate Region; SW = Southwest Hydroclimate Region.

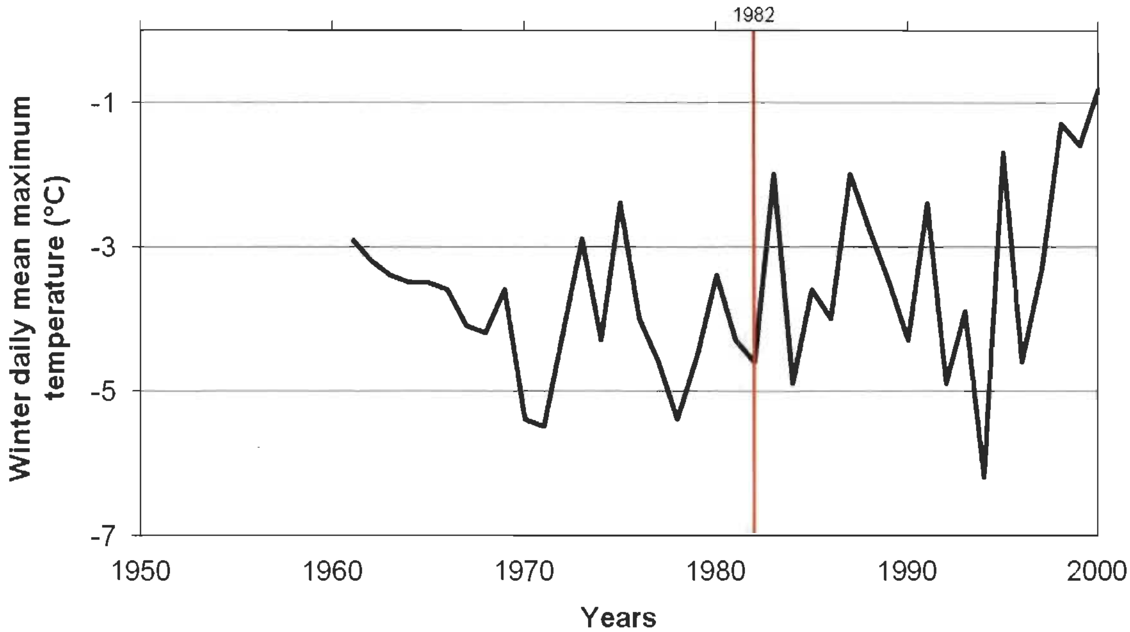

Figure 2. Temporal variability of winter daily mean maximum temperature at the Shawville station. This variability is characterized by a significant increase in mean temperature. Vertical bar shows year of the shift in mean values.

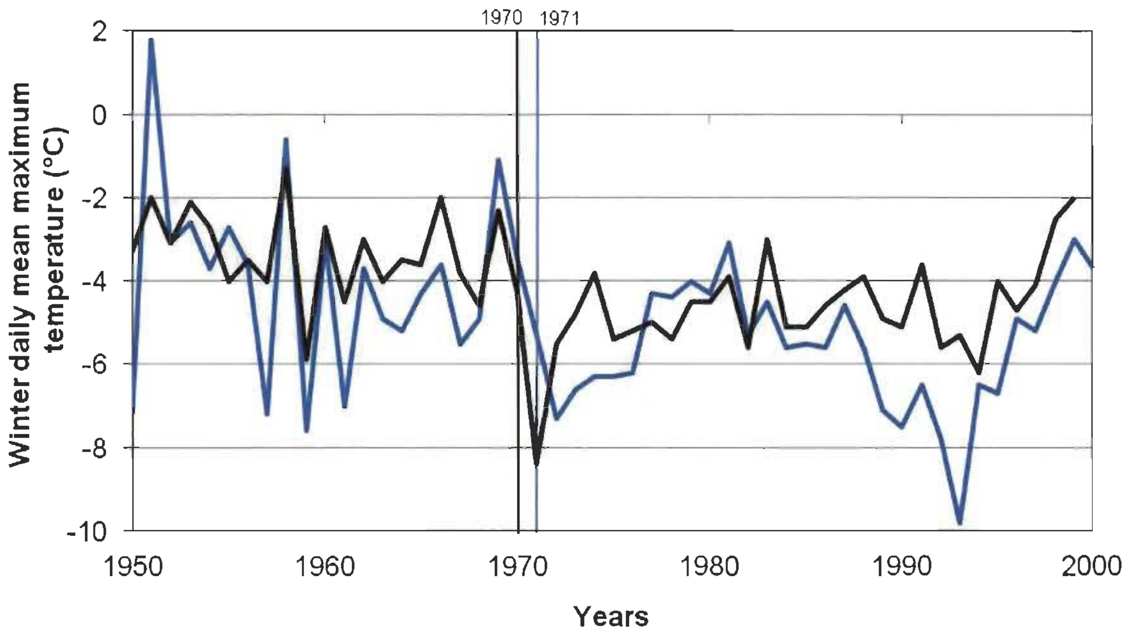

Figure 3. Temporal variability of winter daily mean maximum temperature at the Natashquan (blue curve) and Sainte-Rose (black curve) stations. This variability is characterized by a significant decrease in mean temperature. Vertical bars show years of the shifts in mean values.

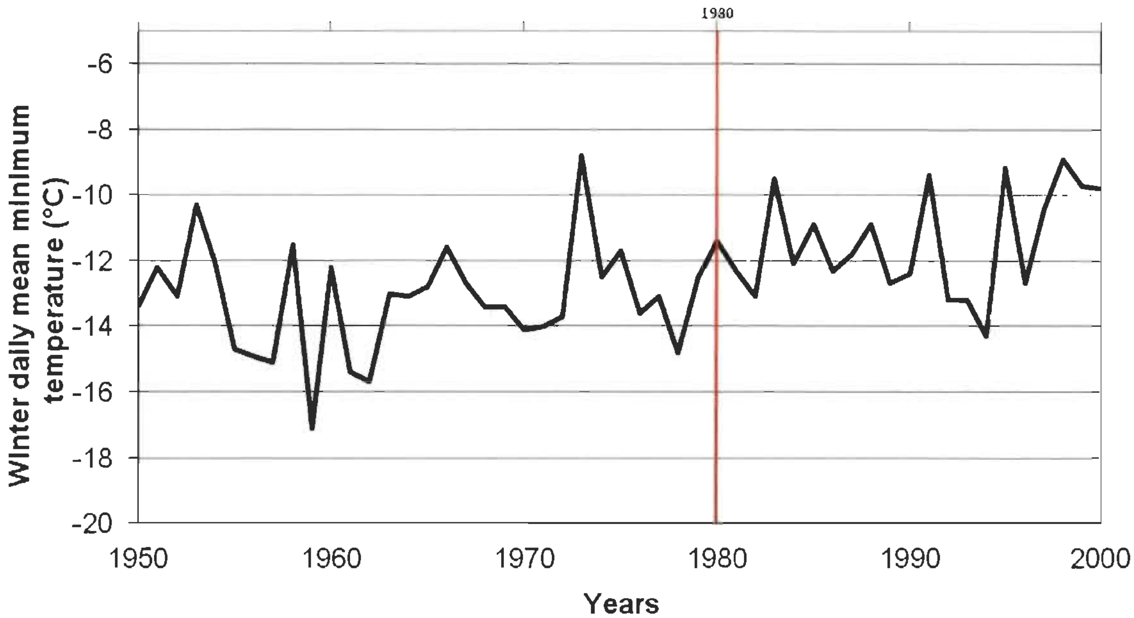

Figure 4. Temporal variability of winter daily mean minimum temperature at the Coaticook station. This variability is characterized by a significant increase in mean temperature. Vertical bar shows year of the shift in mean values.

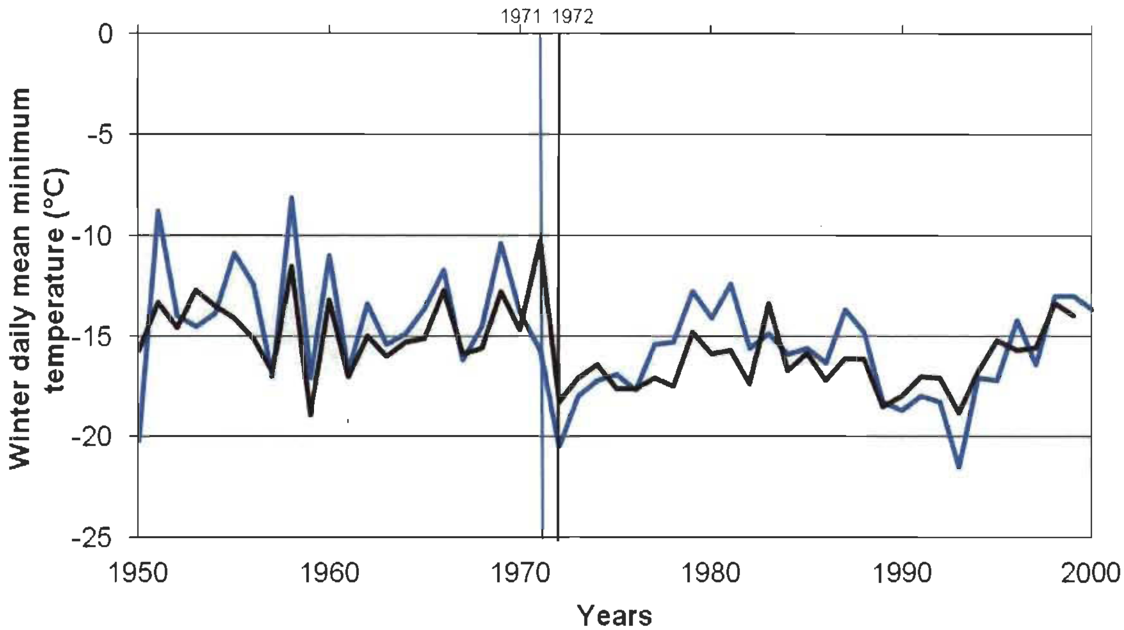

Figure 5. Temporal variability of winter daily mean minimum temperature at the Natashquan (blue curve) and Sainte-Rose (black curve) stations. This variability is characterized by a significant decrease in mean temperature. Vertical bars show years of the shifts in mean values.

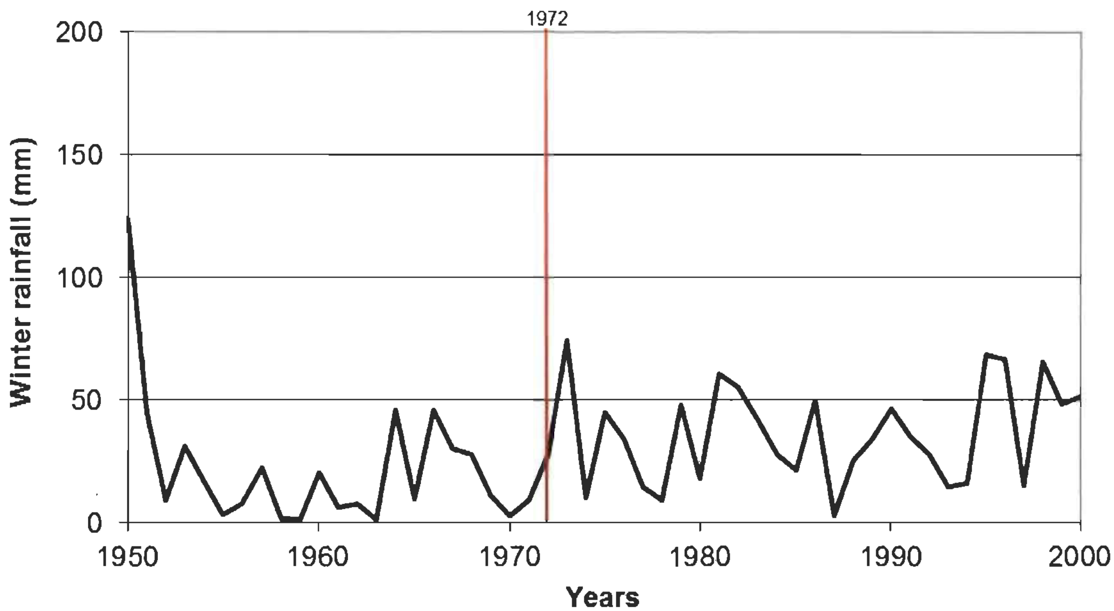

Figure 6. Temporal variability of winter rainfall at the Bagotville station. This variability is characterized by a significant increase in rainfall. Vertical bar shows year of the shift in mean values.

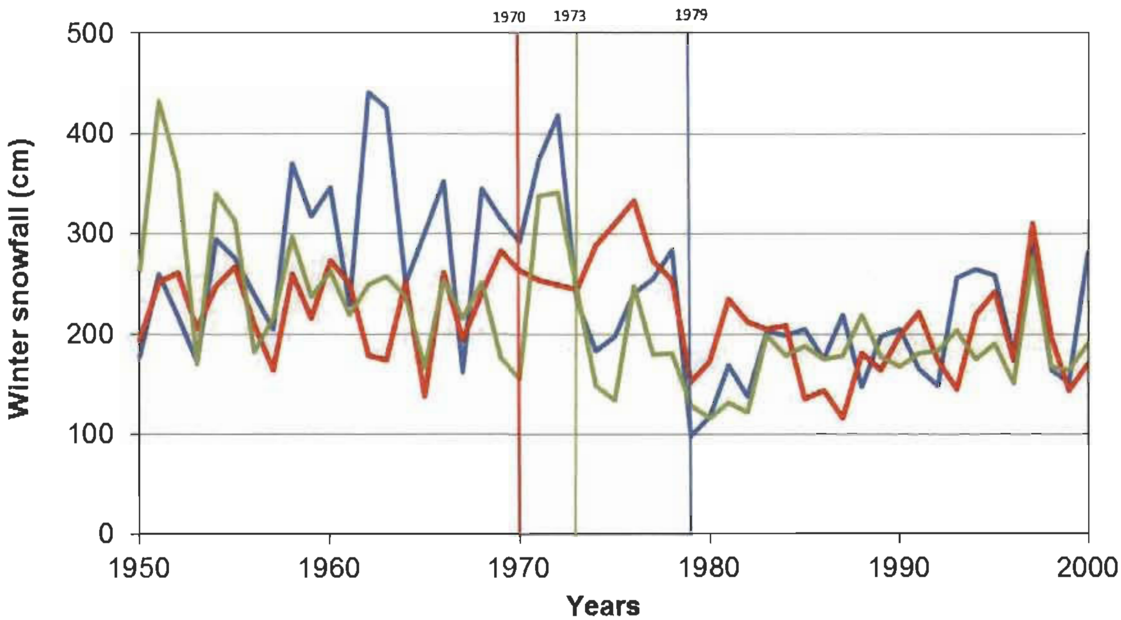

Figure 7. Temporal variability of winter snowfall at the Magog (blue curve) Sainte-Rose (red curve) and Saint-Alban (green curve) stations. This variability is characterized by a significant decrease in snowfall. Vertical bars show years of the shifts in mean values.

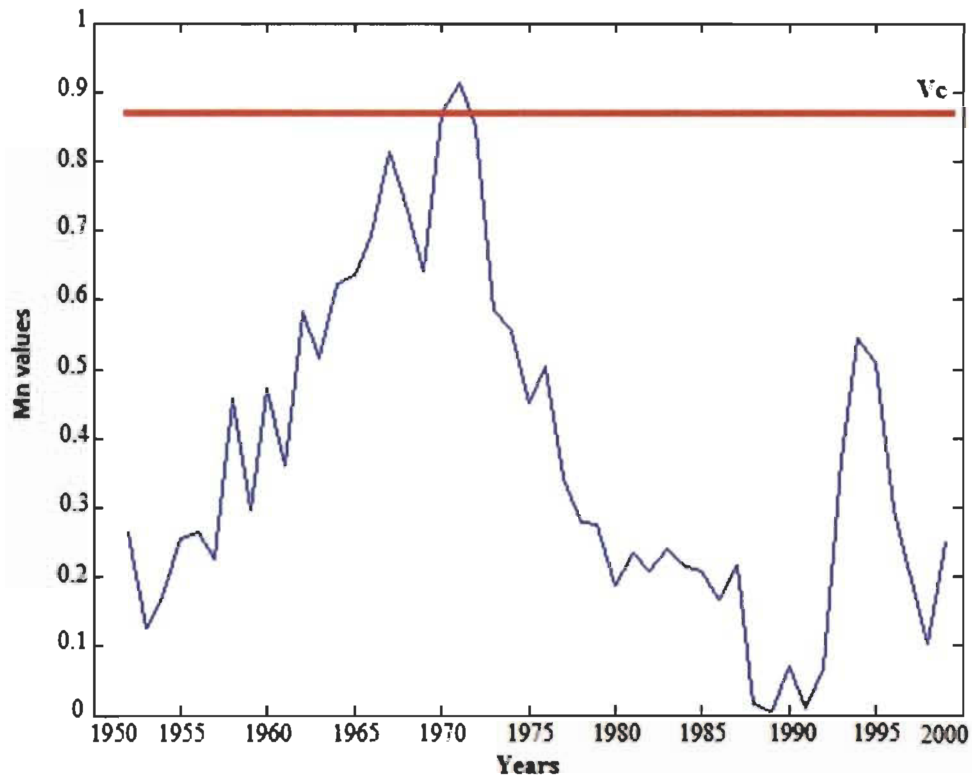

Figure 8. Temporal variability of Mn values calculated between winter daily mean maximum temperature and winter snowfall at Sept-îles station. The change of dependence between the two variables took place in 1972.

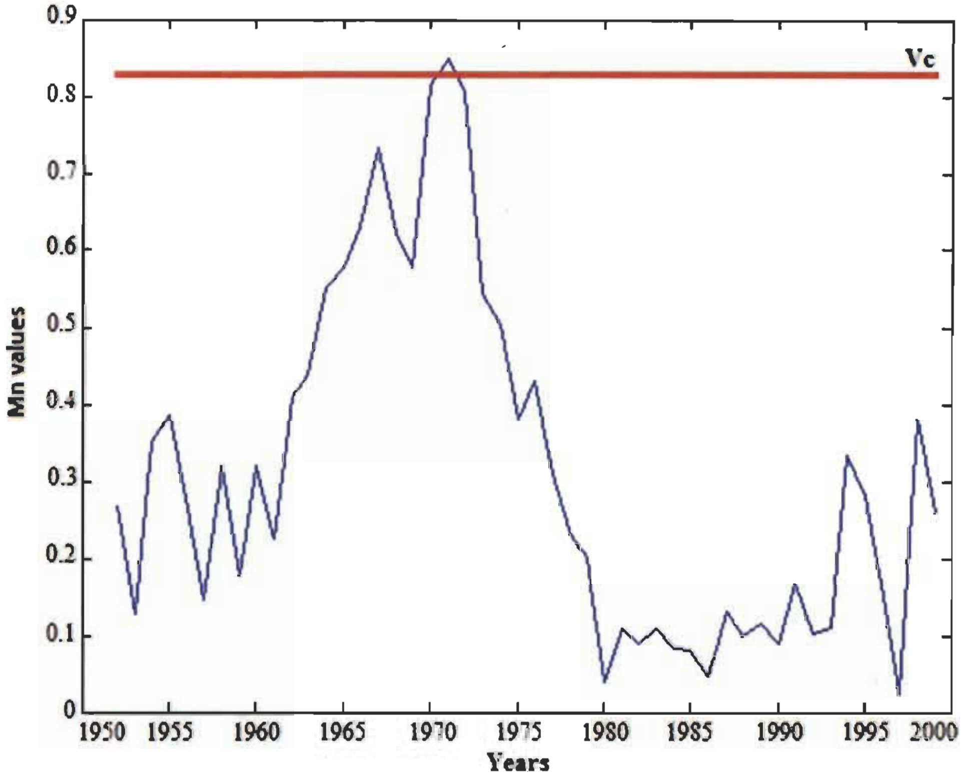

Figure 9. Temporal variability of Mn values. calculated between winter daily mean minimum temperature and winter snowfall at Sept-îles station. The change of dependence between the two variables took place in 1972.

CHAPITRE III

ANALYSIS OF THE JOINT LINK BETWEEN EXTREME TEMPERATURES, PRECIPITATION AND CLIMATE INDICES IN WINTER IN THE THREE HYDROCLIMATE REGIONS OF SOUTHERN QUEBEC

Ce chapitre est présenté sous forme d'article, en anglais, et a été soumis dans la revue *Theoretical and applied climatology* (Nadjet **Guerfi**, Ali A. **Assani**, Raphaëlle **Landry**, Mhamed **Mesfoui**) sous le titre : « Analysis of the joint link between extreme temperatures, precipitation and climate indices in winter in southern Quebec using a new canonical correlation analysis approach ».

Analysis of the joint link between extreme temperatures, precipitation and climate indices in winter in the three hydroclimate regions of southern Quebec

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Abstract

We analyze the relationship between four climate variables (maximum and minimum extreme temperatures, rainfall and snowfall) measured in winter (December to March) at 17 stations from 1950 to 2000 in the three hydroclimate regions of southern Quebec and six seasonal climate indices using canonical correlation analysis and the copula method. This analysis yielded these major results: (1) extreme temperatures are not correlated with the amount of winter rain or snow in southern Quebec; (2) winter seasonal climate indices show better correlations with climate variables than do fall climate indices; (3) winter extreme temperatures are best correlated (positive correlation) with the Atlantic Multidecadal Oscillation (AMO) in the eastern region, but show a negative correlation with the Arctic Oscillation (AO) in the southwestern region; (4) the total amount of winter snow is best correlated (negative correlation) with the Pacific Decadal Oscillation (PDO) in the three hydroclimate regions; (5) the total amount of winter rain is best (negatively) correlated with PDO in the eastern region, but shows a positive correlation with AO in the southeast region. Finally, the copula method revealed very little change in the dependence between climate indices and climate variables in the three hydroclimate regions.

Keywords: winter, extreme temperature, rain, snow, climate index, canonical correlation analysis, copula, southern Quebec

Introduction

A number of studies have analyzed the relationship between climate indices and winter climate variables (temperature and precipitation) in Canada and Quebec (e.g., Assani *et al.*, 2008; Ault and St. George, 2010; Bonsal *et al.*, 2001; Brown, 2010; Coulibaly, 2006; Kingston *et al.*, 2006; Lin *et al.*, 2010; Lu *et al.*, 2011; Montroy *et al.*, 1998; Qian *et al.*, 2008; Rodionov and Assel, 2000; Shabbar, 2006; Shabbar e*t al.*, 1997a, 1997b, 2001; Shabbar and Bonsal, 2003, 2004; Shabbar and Khandekar, 1996; St. George *et al.*, 2010; Stone *et al.*, 2000). These studies raise five types of questions which have not been completely resolved:

1. All these studies analyze temperature and precipitation (rain and snow) separately. As a result, the relationship between these two climate variables in winter remains unknown. This knowledge is important because numerous climate models predict an increase in the amount of winter rain at the expense of winter snow as a result of increasing temperature (e.g., Boyer *et al.*, 2010). While this prediction is based on the assumption that temperature, rain and snow in winter are related, this has never been tested.

2. As far as precipitation is concerned, all the studies cited above look only at the total amount of precipitation (rain and snow combined) in winter, even though rain and snow are known not to be related to the same types of air masses, rain being linked with warm humid air masses and snow, with cold air masses. Hence, it is important to establish whether the total amounts of winter rain and of winter snow are affected by the same climate indices in Quebec in winter. Moreover, from a hydrologic standpoint, the two types of precipitation do not produce the same types of impacts on seasonal streamflow in Quebec. For instance, the amount of winter snow affects minimum flows much more strongly than the total amount of rain; and whereas the amount of rain affects the magnitude of winter, summer and fall floods, it is the amount of snow that affects the magnitude of spring floods in southern Quebec.

3. There is some debate over which climate index is the main influence on the temporal variability of winter temperature and precipitation (snow and rain) in Quebec. Some

authors argue that the El Niño/Southern Oscillation is the main cause of this variability (e.g., Shabbar, 2006; Shabbar *et al.*, 1997a, 1997b), while others believe it is the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) (e.g., Kingston *et al.*, 2006; Qian *et al.*, 2008), the Pacific Decadal Oscillation (PDO) (Brown, 2010) or the Pacific/North American Oscillation (PNA) (Stone *et al.*, 2000).

4. There is also some debate about the choice of seasonal climate index type that best correlates with winter temperature and precipitation. While some authors use fall climate indices, others prefer winter climate indices.

5. While most of these studies have highlighted changes in stationarity (long term trend, change in mean values) of temperature and precipitation series (e.g., Yagouti *et al.*, 2008; Zhang *et al.*, 2000), none has focused on the impacts of these changes in stationarity on the evolution of the dependence between climate indices and climate variables, an aspect of prime importance in the current climate change context.

This study aims to address these five issues in order to provide a better understanding of winter temperature and precipitation patterns in southern Quebec. To this end, we apply canonical correlation analysis and copula method. No previous study has used this approach to examine the relationship between temperature, precipitation and climate indices in southern Quebec.

Methods

Choice and location of stations

In order to analyze the largest possible number of stations, the study was restricted to the period from 1950 to 2000. Very view measurements of climate variables at a large number of stations are available prior to 1950. After 2000, climate variable measurements stopped at many stations, likely as a result of funding cuts resulting from program revision by the Government of Canada during the 1990's (Pilon *et al.*, 1996). We selected every station for which temperature and precipitation measurements were taken for at least 40 years during the study period (1950-2000). In total, 17 stations spread out nearly evenly throughout the southern part of the Province of Quebec (Fig. 1 and Table 1) were selected. These 17 stations were subdivided into three hydroclimate regions defined for southern Quebec using principle component analysis of hydroclimate variables. These are the southeast and eastern region, primarily located on the south shore of the St. Lawrence River, and the southwestern region, located on the north shore (e.g. Assani *et al.*, 2011, 2013). Temperature and precipitation (rain and snow) data were taken from the Environment Canada web site (http://www.climate.weatheroffice.ec.gc.ca/, viewed in March 2011). These data are from Environment Canada's Canadian Daily Rehabilitated Database (e.g. Mekis and Hogg, 1999; Vincent and Gullet, 1999; Vincent and Zhang, 2002). The quality of winter data is generally good, although there are some breaks in data continuity for some stations (Kingston *et al.*, 2006).

Six climate indices were selected that have been shown to influence the spatial and temporal variability of temperature and precipitation in Quebec in particular, and North America in general (e.g., Coulibaly, 2006; Kingston *et al.*, 2006; Qian *et al.*, 2008; Shabbar, 2006). These are the Atlantic Multidecadal Oscillation (AMO), the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), the Pacific/North American Oscillation (PNA) and the Southern Oscillation (SOI). Data for these indices were taken from the NOAA web site http://www.cdc.noaa.gov/ClimateIndices/List (viewed on March 23, 2011).

Statistical analysis

Variable (temperature and precipitation) and climate index series

Two temperature series were assembled, namely daily extreme maximum and minimum temperatures. These two series consist respectively of mean values of daily maximum (Tmax) and minimum (Tmin) temperatures measured from December to March during the period from 1950 to 2000. Two precipitation series were also assembled: a rainfall series and a snowfall series. Both series are comprised of the total daily sum, respectively, of rainfall (RT) and snowfall (ST) measured from December to March during the period from 1950 to 2000. It should be mentioned that, in southern Quebec, depending on the region, winter starts in December and ends in March.

Fours series were assembled for each climate index, including two for fall and two for winter. For fall, the first series consists of monthly means for the months of October to December (OND), and the second series, of monthly means for the months of September to December (SOND). For winter, the first series consists of monthly means for the months of January to March (JFM), and the second series, of monthly means for the months of December to March (DJFM).

Canonical analysis

Canonical correlation analysis (CCA) is widely used in climatology and hydrology to explore the links between two sets of variables (e.g., Wilks, 2013). This method, which is extensively described in the literature (e.g., Afifi and Clark, 1996), is generally used for large data matrices (> 100). In our study, the maximum number of years for which climate variables have been measured is 51, which statistically does not lend itself to canonical multivariate analysis. To get around this technical problem, we grouped all stations from a given hydroclimate region into a single matrix. Thus, for each hydroclimate region, canonical analysis was applied to a matrix for which the number of rows is the product of the number of stations in the region and the number of years of climate variable measurement at each station, and the number of columns is the sum of the five climate variables and six climate indices (11 columns in total). The main advantage of this approach is that it allows simultaneous correlation of multiple climate indices with multiple climate variables measured at different stations. In addition, the analysis of stations with differing numbers of years of observations is also possible. This is what makes this study novel. As a result, there is no loss of information that would otherwise result from grouping stations in homogeneous climate regions, a commonly used approach in climatology to analyze the temporal variability of climate variables. In addition, with the temporal approach, it is possible to include stations for which data for some years are missing, thus optimizing the use of available measurement data for the different stations. Finally, unlike the regionalization approach, the temporal approach can be used to analyze simultaneously multiple climate variables. It should be recalled that canonical analysis is used to relate a group of dependent variables Y (in the present case, five climate variables) and a group of independent variables X (in the present case, six climate indices). These two groups will be replaced, respectively, by new canonical variables V and W. Correlations will be derived between the new canonical variables on one hand, and the original variables and new canonical variables of each group, on the other hand.

Copula analysis

The copula analysis is used to constrain the evolution of the dependence between two variables. Some variables may show changes in mean or variance over time (change in stationarity). This type of change may have a significant effect on the dependence between two variables over time. However, studies in the literature based on the correlation between climate variables and climate indices never take into account the possible impact of this type of change on the dependence between variables. In the present study, the copula method was used to analyze potential changes that may have occurred over time in the dependence between climate indices and climate variables. The use of this method in climatology remains very limited.

The dependence in a random vector (X, Y) is contained in its corresponding copula function C. Specifically, the celebrated theorem of Sklar (1959) ensures that there exists a unique $C : [0, 1]^2 \longrightarrow [0, 1]$ such that

$$P(X \leq x, Y \leq y) = C\{P(X \leq x), P(Y \leq y)\}. \quad (1)$$

Quessy *et al.* (2012) developed a testing procedure to identify a change in the copula (*i.e.* dependence structure) of a bivariate series $(X_1, Y_1), \ldots, (X_n, Y_n)$. The idea is based on Kendall's tau, which is a nonparametric measure of dependence. Let $\hat{T}_{1:T}$ be Kendall's tau measured for the first T observations and $\hat{T}_{T+1:n}$ be Kendall's tau for the remaining $n-T$ observations. The proposed test statistic is

$$M_n = \max_{1<T<n} \frac{T(n-t)}{n\sqrt{n}} \left| \hat{T}_{1:T} - \hat{T}_{T+1:n} \right| \quad (2)$$

i.e. a maximum weighted difference between the Kendall's tau. Since M_n depends on the unknown distribution of the observations, the so-called multiplier re-sampling method is used for the computation of *p*-values. Specifically, for n sufficiently large ($n > 50$), this method yields independent copies $M_n^{(1)},...M_n^{(N)}$ of M_n. Then, a valid *p*-value for the test is given by the proportion of $M_n^{(i)}$'s larger than M_n. For more details, see Quessy *et al.* (2012). Usually, one can expect that the series $X_1, \ldots, X_n$ and $Y_1, \ldots, Y_n$ are subject to changes in the mean and / or variance following, e.g. the smooth-change model (Lombard, 1987). If such changes are detected, the series must be stabilized in order to have (approximately) constant means and variances. Finally, a change in the degree of dependence between two series is statistically significant when $M_n > Vc$, where Vc is the critical value derived from observational data. This method was applied to constrain changes in dependence between those climate indices best correlated with temperature and winter precipitation at each station in the three hydroclimate regions. For theoretical reasons (see Quessy *et al.*, 2012), the copula method was only applied to stations for which the number of years over which measurements were taken is ≥ 50.

Results

Analysis of the relationship between climate variables and climate indices

Canonical coefficient values derived from data matrices using fall and winter climate indices are compared in Table 2. Results for quarterly fall indices (SON) are similar to those for seasonal fall indices (SOND, calculated over four months) presented in Table 2, and the same is true for winter climate indices. For this reason, only results for the SOND and DJFM indices are presented. It can be seen from Table 2 that canonical coefficient of correlation values (r) calculated with winter indices are generally higher than those calculated with fall indices in the three hydroclimate regions, implying that winter indices are better correlated with the four climate variables than fall indices. In addition, in the three hydroclimate regions, the number of statistically significant canonical axes is higher for winter than for fall. From a statistical as well as a climate standpoint (data interpretation), results obtained with winter climate indices appear more interesting than those obtained with fall climate indices. Finally, the number of statistically significant canonical axes varies between regions for winter climate indices. In the eastern hydroclimate region, only the first two axes are statistically significant at the 5% level, while three and four axes are significant, respectively, for the southeast and southwestern regions. For the southeast region, however, the last axis is statistically significant at the 10% level.

The two types of seasonal indices lead to the same results in terms of the relationships between climate variables and climate indices. Due to these similar results, we only interpret results derived with winter climate indices in order to limit the number of tables to analyze and any redundancy in the results. The structure coefficients derived using winter climate indices are shown in Tables 3, 4 and 5 for the three hydroclimate regions.

For the eastern region (Table 3), only the first two canonical axes are statistically significant (see Table 2). It follows that V1 and V2 on one hand, and W1 and W2 on the other hand are statistically significant canonical variables. V1 is positively correlated with maximum and minimum temperatures and V2 is correlated, albeit moderately, to precipitation (snow and rain). For the canonical variables extracted from the climate index data matrix, W1 is positively correlated with AMO, but negatively correlated with AO. W2 is negatively correlated with PDO. Since V1 is correlated with W1 and V2 is correlated with W2, it follows that maximum and minimum temperatures are positively correlated with AMO and, to a lesser extent, negatively correlated with AO. Precipitation is negatively correlated with PDO.

In the southeast region (Table 4), the first three canonical axes are statistically significant (see Table 2). It can be seen from Table 4 that V1 is positively correlated with maximum and minimum temperatures and V2 is negatively correlated with rainfall. The amount of snow is correlated with V4, the canonical axis of which is significant at the 10% level. While the W1 canonical variable is not significantly correlated with any climate index, W2 is negatively correlated with AO. The last canonical variable, W3, is not correlated with any of the climate indices. W4 is positively correlated with PDO. Unlike the previous hydroclimate region, temperatures in the southeast region are not correlated with any climate index.

In the southwest region (Table 5), V1 is positively correlated with maximum temperature, V2 and V3 are negatively correlated, respectively, with the amounts of snow and rainfall, and V4 is positively correlated with minimum temperature. W1 is not significantly correlated with any climate index. In contrast, W2 is positively correlated with PDO and PNA, but negatively correlated with SOI. W1 and W3 are not correlated with any climate index. W4 is negatively correlated with AO. Therefore, the total amount of winter snow is strongly correlated with PDO, and minimum temperature is correlated with AO. The other two climate variables are not correlated with any climate index. Table 6 presents a summary of canonical correlation analysis results.

This analysis reveals that PDO is the only climate index that influences the amount of winter snow in the three hydroclimate regions. Temperatures and amount of rain are correlated with different climate indices depending on the region.

Analysis of the evolution of the dependence between climate indices and climate variables

Copula method results are shown in Tables 7, 8 and 9 as well as in Figures 2, 3, and 4. In the eastern region, changes in dependence are observed for two stations, the Bagotville station (dependence between PDO and SNT) and the Mont-Joli station (dependence between AMO and Tmin). In the southeast region, a change is observed at the Saint-Malo station (AO and RNT). Finally, in the southwest region, no change is observed in the dependence between climate indices and climate variables.

Discussion and conclusion

Canonical correlation analysis (CCA) was used to analyze simultaneously the correlation between winter temperature and precipitation (climate variables) on one hand, and their correlation with six climate indices, on the other. The first original contribution of this study is the use of the CCA method to simultaneously analyze the correlation between temperature, precipitation and climate indices measured at multiple stations over all the years of measurement. In this way, no information is lost by first grouping the stations (through principal component analysis or hierarchical classification, for instance) into homogeneous climate regions. The second original contribution of the study is the use of the copula method to constrain changes in dependence between climate indices and climate variables over time. Results obtained using these two methods contribute to a better understanding of controversial issues relating to winter climate patterns in southern Quebec. The study yielded the following notable results:

1. As regards the selection of seasonal climate indices that are best correlated with climate variables, canonical analysis showed that winter climate indices are better correlated with winter temperature and precipitation in the three hydroclimate regions in southern Quebec. Thus, winter indices yielded generally higher canonical correlation coefficients and a larger number of statistically significant canonical axes then fall climate indices. In a climate perspective, winter climate conditions are therefore primarily influenced by winter climate indices.

2. As regards the relationship between the various climate variables (temperature and precipitation), the study shows that there is no statistically significant correlation between winter temperature and precipitation in Quebec. Thus, maximum and minimum temperatures correlated with one another are not correlated with the amount of rain or snow. A commonly accepted assumption is that increasing winter

temperature induces a decrease in the amount of snow and a concomitant increase in the amount of rain in winter. However, the link between temperature and amount of precipitation is not as simple as commonly suggested. From a climate standpoint, the amount of snow or rain in winter does not depend exclusively on air temperature variability. Three other factors are also important: the amount of water vapor available in the atmosphere, the frequency and magnitude of convective movements, and the frequency and persistence of cold and warm air masses. In Quebec, winter rainfalls are associated with the presence of warm and humid air masses coming from the United States and/or the Atlantic Ocean. However, the amount of rain produced by these warm and humid air masses during a given season depends primarily on their frequency in the region and the amount of water vapor they contain. Hence, although it has been shown that winter temperatures in Quebec are on the rise, this warming does not necessarily lead to higher rainfall in winter, because this temperature increase affects minimum nighttime temperatures much more strongly than it does maximum daytime temperatures (Yagouti *et al.*, 2008). In winter, although minimum temperatures are increasing, they still most commonly fall below 0°C, which precludes an increase in the amount or frequency of precipitation as rain during winter in Quebec. Finally, the impact of this nighttime warming on the increased frequency of warm and humid air masses that produce rain has yet to been demonstrated in Quebec. The amount of snow in winter in Quebec primarily depends, for its part, on the frequency of cold fronts associated with cyclogenesis (polar front). However, this frequency is independent of the nighttime warming observed in Quebec as such, because these fronts are part of larger regional and global scale air mass patterns. This may account for the absence of any significant relationship between temperature and amount of snow in Quebec.

3. As regards the link between climate variables (temperature and precipitation) and climate indices, the study reveals that temperature and precipitation during winter in Quebec are not correlated with the same climate indices. In other words, they are not affected by the same climate factors, which may in part account for the absence of correlation observed between the two climate variables. For temperature, canonical analysis showed that maximum and minimum temperatures are best positively

correlated with AMO only in the eastern region, which has a maritime-like climate. In the southeast region, temperatures are not correlated with any climate index, while in the southwest region, only minimum temperatures show a better negative correlation with AO. AMO describes the temporal variability of Atlantic Ocean surface temperatures in the Northern Hemisphere. This positive correlation suggests that, when Atlantic surface water temperatures are above normal (positive anomaly), maximum and minimum temperatures during winter in Quebec increase, likely as a result of energy transfer from the ocean to the North American continent. Incidentally, the effect of this climate index on the temporal variability of rainfall and streamflow has already been described for numerous regions of North America (e.g. Curtis, 2008; Enfield *et al.*, 2001; McCabe *et al.*, 2004, Sutton and Hodson, 2005). As far as AO is concerned, its influence on temperature, precipitation and streamflow in rivers in the northeastern part of North America has already been described by Kingston *et al.* (2006). According to these authors, this influence in eastern Canada is due to the fact that when this index is in a positive phase in winter, temperatures are below normal (negative correlation) due to stronger polar air in the region. However, the influence of this climate index does not seem to affect the whole south shore (eastern and southeast regions) of the St. Lawrence River.

4. As regards total winter rain, they show a better negative correlation with PDO in the eastern region, but a positive correlation with AO in the southeast region. This latter positive correlation goes against the explanation proposed by Kingston *et al.* (2006). Finally, PDO is the only climate index that shows a better negative correlation with the total amount of snow in all three hydroclimate regions. Brown (2010) observed a strong negative correlation between PDO and the total duration of snow cover in the fall in the western part of southern Quebec. However, the climate mechanisms whereby PDO influences the amount of snow in Quebec remain unclear. It is possible to speculate, however, that this climate index may influence the frequency of polar front-related low pressure systems in the region, since snow precipitations in Quebec are caused by such low pressure systems.

5. The lack of stationarity observed in temperature and winter precipitation series from Quebec (e.g., Yagouti *et al.*, 2008; Zhang *et al.*, 2000) has had very little effect on the evolution of the dependence between climate indices and climate variables.

In summary, the study highlights the fact that PDO is the only climate index that influences the amount of snow in winter throughout Quebec, although the climate mechanisms that account for this influence remain unclear. At the scale of the province, temperatures and the total amount of rain in winter are not correlated with the same climate indices.

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Table 1. Climatic stations.

Code	Station	ID	Altitude (m)	Latitude (N)	Longitude (W)	Years
SE1 (1)	Coaticook	7021840	259	45°09'	71°48'	51
SE2 (2)	Granby	7022802	168	45°23'	72°42'	47
SE3 (3)	Magog	7024440	274	45°16'	72°07'	51
SE4 (4)	Montréal	7025250	36	45°28'	73°45'	51
SE5 (5)	Philipsburg	7026040	53	45°02'	73°05'	51
SE6 (6)	St Malo d'Auckland	7027520	564	45°12'	71°30'	51
E1 (7)	Bagotville	7060400	159	48°20'	71°00'	51
E2 (8)	Mont Joli A	7055120	48	48°36'	68°13'	51
E3 (9)	Natashquan A	7045410	575	48°57'	65°31'	51
E4 (10)	Sept Iles A	7047910	310	50°13'	66°16'	51
E5 (11)	Ste Rose du Degelis	7057720	151	47°34'	68°38'	50
E6 (12)	Trois-Pistoles	7058560	58	48°09'	69°07'	49
SW1 (13)	Chelsea	7031660	112	45°31'	75°47'	51
SW2 (14)	Nominingue	7035520	305	46°23'	75°03'	51
SW3 (15)	Shawville	7038040	168	45°37'	76°28'	40
SW4 (16)	St Alban	7016800	76	46°43'	72°05'	51
SW5 (17)	St-Michel-Des-Saints	7077570	350	46°41'	73°55'	43

Table 2. Comparison of canonical correlation coefficients (R) as a function of seasonal climate indices.

Canonical axes	Winter climate indices (DJFM)			Fall climate indices (SOND)		
	r	F	P>F	r	F	P>F
			East region			
CC1	0.524	5.92	**<.0001**	0.485	4.83	**<.0001**
CC2	0.324	2.66	**0.0006**	0.261	2.13	**0.0074**
CC3	0.134	0.80	0.5985	0.176	1.33	0.2258
CC4	0.060	0.36	0.7830	0.065	0.42	0.7416
			Southeast region			
CC1	0.515	7.03	**<.0001**	0.445	3.67	**<.0001**
CC2	0.389	4.62	**<.0001**	0.183	1.35	0.1662
CC3	0.197	2.35	**0.0171**	0.144	1.26	0.2601
CC4	0.152	2.34	0.0739	0.114	1.31	0.2723
			Southwest region			
CC1	0.539	6.25	**<.0001**	0.574	4.71	**<.0001**
CC2	0.399	4.21	**<.0001**	0.196	1.04	0.4076
CC3	0.235	2.68	**0.0069**	0.136	0.83	0.5754
CC4	0.187	2.75	**0.0433**	0.102	0.80	0.4929

r = correlation between canonical axes (CC). * = statistically significant r values at the 5% probability level are shown in bold.

Table 3. Structure coefficients derived using winter seasonal climate indices for Eastern Region.

Variables	V1	V2	V3	V4	W1	W2	W3	W4
Tmax	**0.950**	0.147	0.211	-0.180				
Tmin	**0.750**	0.048	0.372	0.547				
RNT	-0.084	**0.636**	0.721	-0.262				
SNT	-0.009	**0.701**	-0.580	0.415				
AMO					**0.837**	-0.013	-0.217	-0.203
AO					**-0.739**	0.222	-0.137	-0.342
NAO					-0.512	0.279	0.127	-0.483
PDO					-0.005	**-0.618**	0.739	-0.244
PNA					0.100	-0.098	0.948	-0.021
SOI					-0.106	-0.030	-0.657	0.587
EV (%)	36.80	22.99	25.98	14.31	25.50	8.66	32.64	13.26

EV = Explained variance; the highest structure coefficient values that are statistically significant at the 5% level are shown in bold.

Table 4 Structure coefficients derived using winter seasonal climate indices for Southeast Region.

Variables	V1	V2	V3	V4	W1	W2	W3	W4
Tmax	**0.956**	0.041	0.146	0.250				
Tmin	**0.641**	0.272	-0.566	0.441				
RNT	0.431	**-0.800**	-0.319	0.268				
SNT	-0.141	0.094	-0.260	**-0.950**				
AMO					0.460	0.423	0.112	0.145
AO					0.341	**-0.722**	0.507	-0.078
NAO					0.520	-0.414	0.266	0.351
PDO					-0.307	-0.120	0.022	**0.842**
PNA					0.164	0.000	0.063	0.570
SOI					-0.160	0.493	0.469	-0.438
EV (%)	38.26	18.11	12.77	30.78	12.41	18.81	9.41	22.93

EV = Explained variance; the highest structure coefficient values that are statistically significant at the 5% level are shown in bold.

Table 5. Structure coefficients derived using winter seasonal climate indices for Southwest region.

Variables	V1	V2	V3	V4	W1	W2	W3	W4
Tmax	**0.857**	0.276	-0.077	0.429				
Tmin	0.383	0.434	-0.354	**0.734**				
RNT	0.283	0.216	**-0.930**	-0.088				
SNT	0.021	**-0.968**	-0.032	0.249				
AMO					0.582	-0.051	0.573	0.311
AO					0.306	-0.089	-0.102	**-0.910**
NAO					0.475	0.300	-0.083	-0.550
PDO					-0.304	**0.903**	0.248	-0.057
PNA					0.153	**0.779**	0.063	0.031
SOI					-0.147	**-0.711**	0.364	0.091
EV (%)	24.04	31.20	24.92	19.81	13.25	33.80	9.05	20.66

EV = Explained variance; the highest structure coefficient values that are statistically significant at the 5% level are shown in bold.

Table 6. Comparison of the link between climate indices and climate variables in the three southern Quebec hydroclimate regions (1950-2000). Summary of canonical correlation analysis results.

Climate variables	Eastern region	Southeast region	Southwest region
Tmax	AMO (+)	-	-
Tmin	AMO (+)	-	AO (-)
RNT	PDO (-)	AO (+)	-
SNT	PDO (-)	PDO (-)*	PDO (-)

These are the climate indices that show the best correlation with climate variables. (+) = positive correlation; (-) = negative correlation.

Table 7. Results of the copula method used to analyze changes in dependence between climate variables and winter climate indices (DJFM) (1950-2000) in the eastern region.

Stations	AMO-Tmax- AMO			AMO-Tmin			RNT-PDO			PDO-SNT		
	Mn	V_C	p-value	Mn	V_C	p-value	Mn	VC	p-value	Mn	V_C	p-value
Bagotville	0.6580	0.7286	0.0840	0.6407	0.8395	0.1870	0.3847	0.7669	0.6780	**0.9512**	**0.8455**	**0.0290**
Mont Joli A	0.5704	0.7745	0.2000	**0.7044**	**0.6942**	**0.0450**	0.6108	0.7689	0.1930	0.8095	0.9051	0.0900
Natashquan A	0.5550	0.7829	0.2670	0.7481	0.8262	0.0940	0.6216	0.8053	0.2170	0.6977	0.8745	0.1730
Sept Iles A	0.6098	0.7502	0.1500	0.6851	0.7956	0.1260	0.6077	0.8419	0.2360	0.6468	0.8078	0.1780
Ste Rose	0.5474	0.7212	0.2300	0.7197	0.7397	0.0620	0.5275	0.8467	0.4430	0.6244	0.7771	0.1730

Significant values are shown in bold.

Table 8. Results of the copula method used to analyze changes in dependence between climate variables and winter climate indices (DJFM) (1950-2000) in the Southeast region.

Stations	Pluie- AO			Neige- PDO		
	Mn	V_C	p-value	Mn	V_C	p-value
Coaticook	0.7505	0.7728	0.0660	0.6200	0.8329	0.2470
Magog	0.8295	0.8492	0.0560	0.7133	0.8265	0.1150
Montréal	0.7503	0.9421	0.1840	0.4785	0.7370	0.4040
Philipsburg	0.6651	0.8833	0.2570	0.5385	0.8427	0.3920
StMalo	**0.9994**	**0.9091**	**0.0230**	0.4434	0.8386	0.6070

Significant values are shown in bold.

Table 9. Results of the copula method used to analyze changes in dependence between climate variables and winter climate indices (DJFM) (1950-2000) in the Southwest region.

Stations	Tmin- AO			Neige- PDO		
	Mn	V_C	p-value	Mn	V_C	p-value
Chelsea	0.3960	0.9349	0.7890	0.4641	0.8345	0.5470
Nominingue	0.6679	0.8877	0.1980	0.7742	0.9119	0.1250
St- Alban	0.4463	0.9276	0.6600	0.4220	0.8826	0.7040

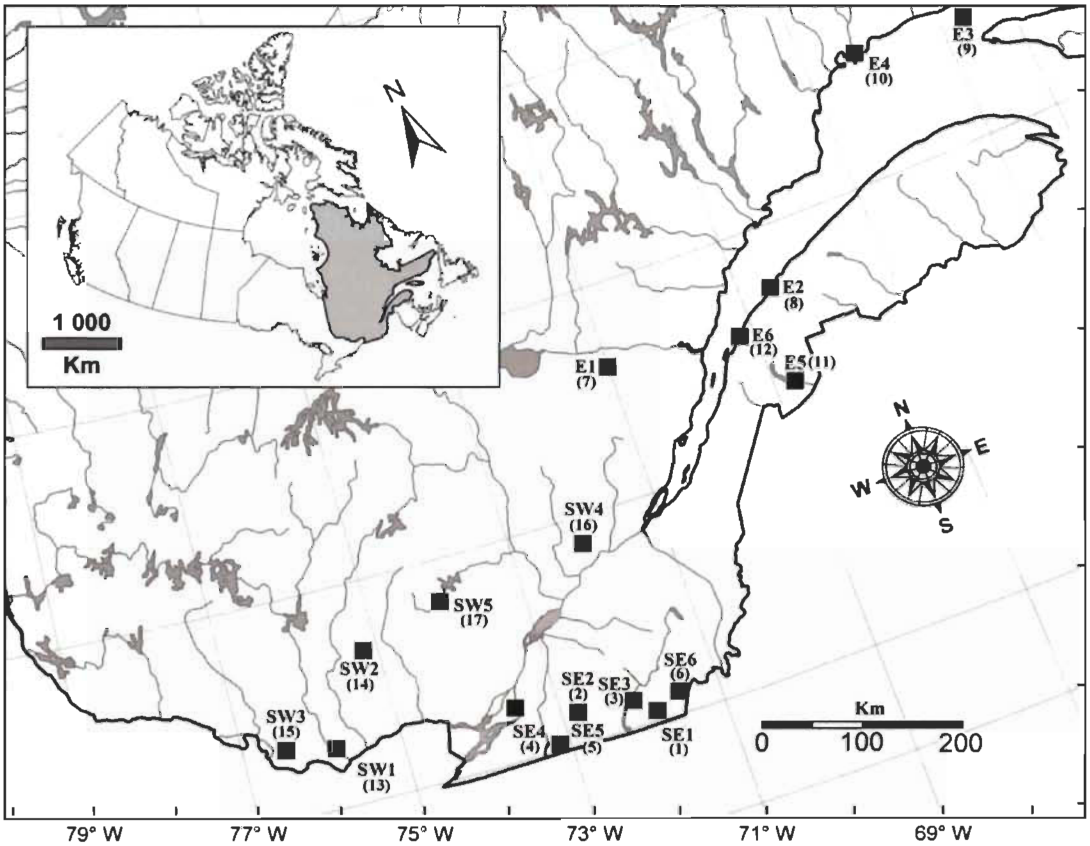

Figure 1. Location of stations.

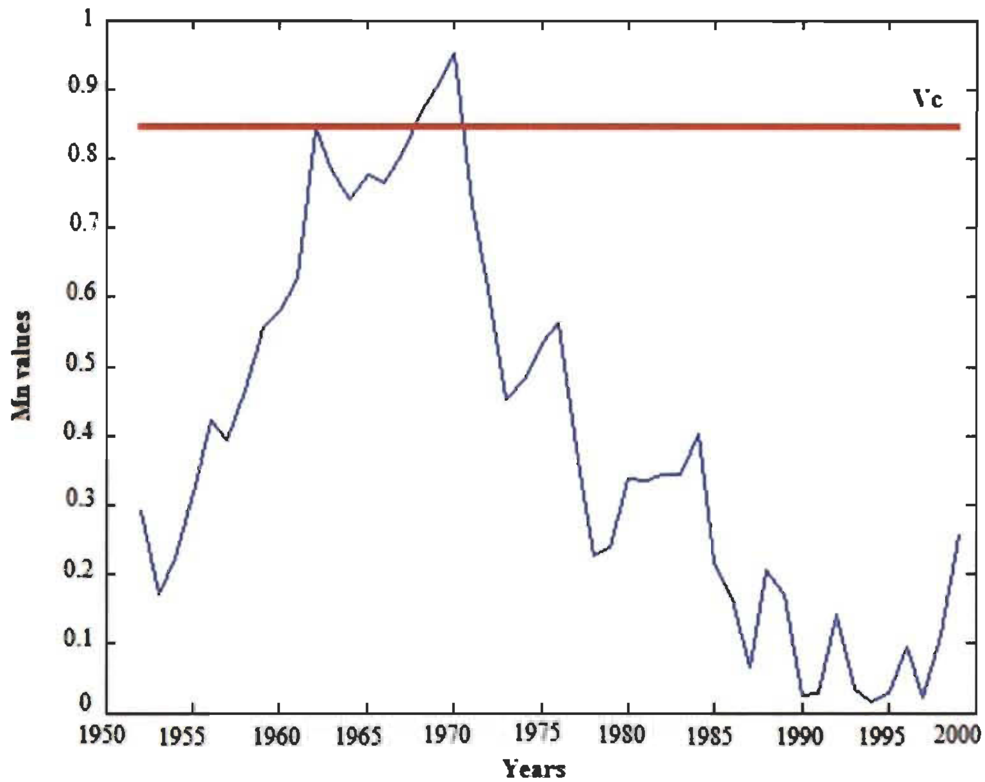

Figure 2. Temporal variability of Mn values derived for the link between PDO and SNT at the Bagotville station (1950-2000).

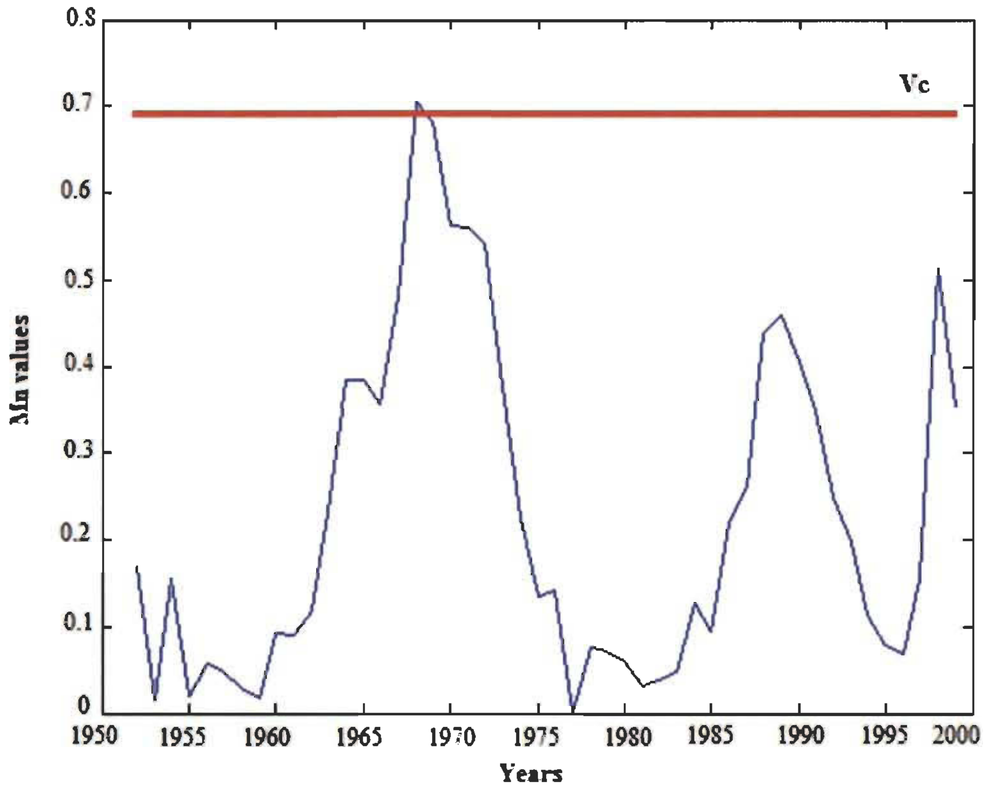

Figure 3. Temporal variability of Mn values derived for the link between AMO and Tmin at the Mont-Joli station (1950-2000).

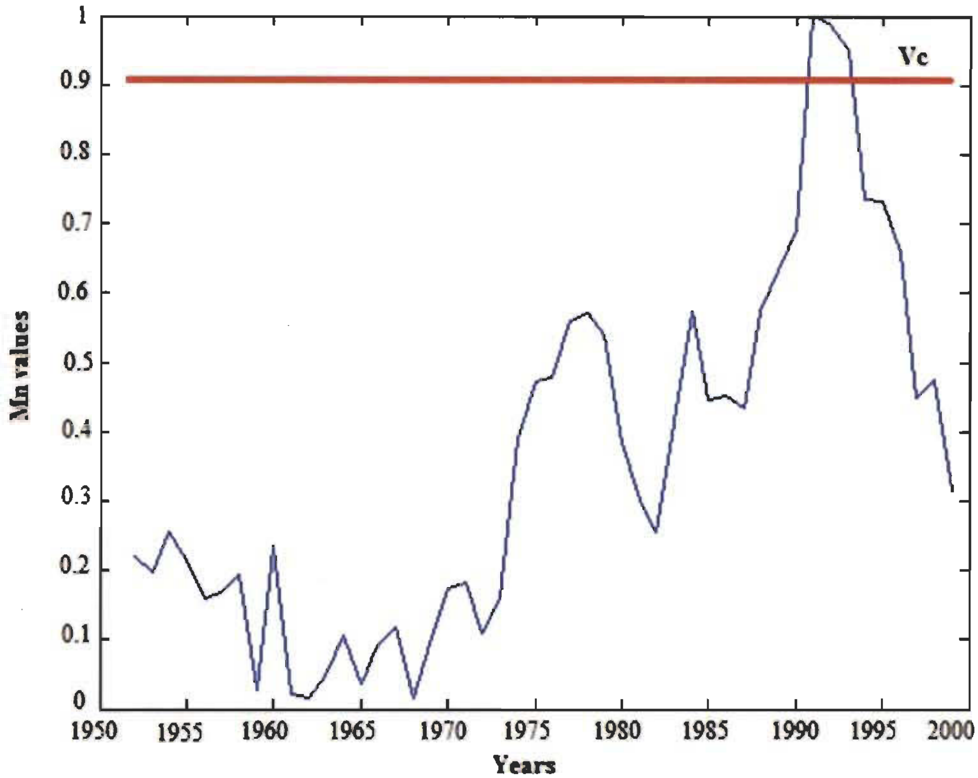

Figure 4. Temporal variability of Mn values derived for the link between AO and RNT at the St-Malo d'Auckland station (1950-2000).

CHAPITRE IV

CONCLUSION GÉNÉRALE

Cette étude a permis d'analyser simultanément la variabilité interannuelle des températures et des précipitations hivernales au Québec méridional ainsi que leurs relations avec les indices climatiques.

Afin de comparer la variabilité interannuelle des températures et des précipitations, nous avons appliqué la méthode de Lombard pour détecter les ruptures des moyennes et celle de copules pour détecter le changement de dépendance entre les variables dans le temps.

En ce qui concerne la rupture des moyennes, l'analyse de 17 stations climatiques pendant la période 1950-2000 a révélé des ruptures des moyennes des températures extrêmes maximales et minimales à trois stations. Quant aux précipitations, les ruptures des moyennes des totaux de pluies et de neige ont été mises en évidence respectivement à 1 et à 7 stations. Pendant la période 1950-2010, l'analyse de 7 stations a révélé des ruptures des moyennes des températures extrêmes maximales et minimales respectivement à 3 et 1 stations. Quant aux précipitations, les ruptures des moyennes des totaux de pluies et de neige ont été observées respectivement à 2 et 3 stations.

Les changements qui affectent la température se traduisent par une diminution significative des valeurs moyennes pour les stations situées au nord de 47 °N, mais une augmentation significative de la température dans les stations situées au sud du 47 °N.

Pour les précipitations, les changements observés reflètent une augmentation significative de la quantité de pluie, mais une diminution de la quantité de neige.

Malgré les ruptures des moyennes des séries des températures et des précipitations observées à plusieurs stations, peu de changements ont été observés sur la dépendance entre ces deux variables climatiques. Pendant la période 1950-2010, aucun changement de dépendance ne fut observé. Pendant la période 1950-2000, le changement de dépendance a surtout affecté la quantité de neige et les températures minimales.

Les résultats obtenus par l'analyse canonique de corrélation ainsi que l'analyse de copules ont contribué à la résolution de quatre problèmes qui font l'objet de controverse sur la dynamique du climat en hiver au Québec méridional. Cette étude a mis en évidence cinq résultats significatifs :

- Les indices climatiques hivernaux sont les mieux corrélés aux températures et aux précipitations hivernales au Québec méridional.

- Il n'existe aucune corrélation statistiquement significative entre la température et les précipitations en hiver au Québec. Ainsi, les températures maximales et minimales qui sont corrélées entre elles ne le sont ni à la quantité des pluies ni à celle de la neige.

- La température et les précipitations ne sont pas corrélées aux mêmes indices climatiques. En d'autres termes, elles ne sont pas influencées par les mêmes facteurs climatiques. Ceci expliquerait en partie l'absence de corrélation observée entre les deux variables climatiques.

- PDO est le seul indice climatique qui influence la quantité de neige en hiver. Les températures et la quantité totale de pluies en hiver ne sont pas corrélées aux mêmes indices climatiques.

- L'absence de stationnarité qui a été observée sur des séries de températures et de précipitations en hiver au Québec a très peu affecté l'évolution du lien de dépendance entre les indices climatiques et les variables climatiques.

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