

The evolution of temperature extremes in the Gaspé Peninsula, Quebec, Canada (1974–2013)

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Abstract The majority of natural hazards that affect Canadian territory are the result of extreme climate and weather conditions. Among these weather hazards, some can be calculated from the application of thresholds for minimum and maximum temperatures at a daily or monthly timescale. These thermal indices allowed the prediction of extreme conditions that may have an impact on the human population by affecting, for example, health, agriculture, and water resources. In this article, we discuss the methods used (RHtestsV4, SPLIDHOM, ClimPACT) then describe the steps followed to calculate the indices, including how we dealt with the problem of missing data and the necessity to identify a common methodology to analyze the time series. We also present possible solutions for ensuring the quality of meteorological data. We then present an overview of the results, namely the main trends and variability of extreme temperature for seven stations located in the Gaspé Peninsula from 1974 to 2013. Our results indicate some break points in time series and positive trends for most indices related to the rise of the temperatures but indicate a negative trend for the indices related to low temperatures for most stations during the study period.

1 Introduction

The recent warming observed at a global scale may be difficult to detect at a regional or local scale, especially when geographical features such as mountains or large bodies of water are located nearby. This is the case for the Gaspé Peninsula, located in the eastern part of the province of Quebec, Canada, where the regional climate is heavily influenced by the Notre-Dame Mountains and St. Lawrence River (Fortin and Hétu, 2014). Climate observations can also be altered by inhomogeneity introduced by human causes like a modification of the environment of the stations (urban development, trees and vegetation growth, etc.), the relocation of weather stations (changes in elevation, latitude, or longitude), and changes in instrumentation, observation methods, and data manipulation (Acquotta and Fratianni 2014; Mestre et al. 2013; Peterson et al. 1998; Peterson 2003; Venema et al. 2012; Vincent et al. 2005). Weather station closures and relocation are the most common issues in the time series for different regions of the world (Alexander et al. 2006; Brunet et al. 2007, 2011; Buishand et al. 2013; Menne et al. 2010; Retchless et al. 2014; Trewin 2013; Wijngaard et al. 2003; Zandonadi et al. 2016) and also for Canada (Vincent et al. 2002; Vincent and Mekis 2004). In order to properly characterize climate variability and detect any significant trends over time, it is necessary to ensure data quality and correct any inhomogeneities in the time series before undertaking climate variability analyses (Domonkos et al. 2012; Drogue et al. 2005; Ducré-Robitaille et al. 2003; Fyfe and Flato 1999). In recent years, much work has been done to address the inhomogeneity problem and different homogenization methods have been proposed (Freitas et al. 2013; Hannart et al. 2014; Menne and Williams 2009; Mestre et al. 2013; Peterson et al. 1998; Venema et al. 2012). In Canada, Zhang et al. 2000 used homogenized temperatures for an analysis of trends in annual and seasonal

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temperature and precipitation while Vincent et al. (2012) studied changes in temperature and precipitation for 338 stations across the country (this is an update of the previous work by Vincent and M  kis 2006 using 210 stations).

The main goal of this study is to characterize the trends for the temperatures indices (based on the minimum and maximum daily temperature) at yearly timescales from seven weather stations located in the Gasp   Peninsula (Quebec, Canada). Two homogenization methods were used to improve the quality of the raw daily data: RHtestsV4 (Wang and Feng 2013) and SPLIDHOM (Mestre et al. 2011). Using these corrected time series, climate indices were then calculated for the period from 1974 to 2013 using ClimPACT software (Alexander et al. 2013).

2 Study area

The study was conducted in the Gasp   Peninsula, located in the province of Quebec, which is in the southeastern part of Canada (Fig. 1). The climate of the region is characterized by the influence of the mountains (Notre-Dame Mountains) and of large bodies of water (the Gulf of St. Lawrence and Chaleur Bay). Mean annual maximum and minimum temperatures (based on the normal from 1981 to 2010 from Environment Canada, 2016a) vary from 8.9 to 7.3   C for the maximum and from -3.2 to 0.1   C for the minimum depending on elevation and distance from the sea. Approximately 30 % of the total precipitation falls as snow, and the total precipitation of 933.2

to 1195.1 mm includes 733 to 811 mm of rain and 269.4 to 387.6 cm of snow.

3 Data and quality control

The data used in this study are the daily maximum and minimum temperatures, from the National Climate Data Archive of Environment Canada (2016a). The stations were selected based on data quality, location, time duration, and the number of missing values. Since the 1990s, the number of weather stations in Canada has decreased (replacement of manual by automatized stations, closures, and relocations). Seven weather stations were used for our study (Fig. 1). During the study period, two stations were relocated nearby (less than 20 km away) so we merged observations at co-located stations to ensure a sufficient number of stations over the study area (Table 1).

The correction of data is an essential step to ensure there are no outliers and that no more than 20 % of the data is missing (see Table 1 for missing data in our data sets) (Acquaotta et al. 2009; Aguilar et al. 2003). The data quality control began with the ClimPACT software package (Alexander et al. 2013) which allowed us to identify outliers and other unrealistic values. In addition, the metadata was used to account for break points in our time series. We found that two stations were relocated (Cap-Madeleine in 1994 and Murdochville in 1995); otherwise, no other potential explanations for the break points found in the time series have been given from the historical research.

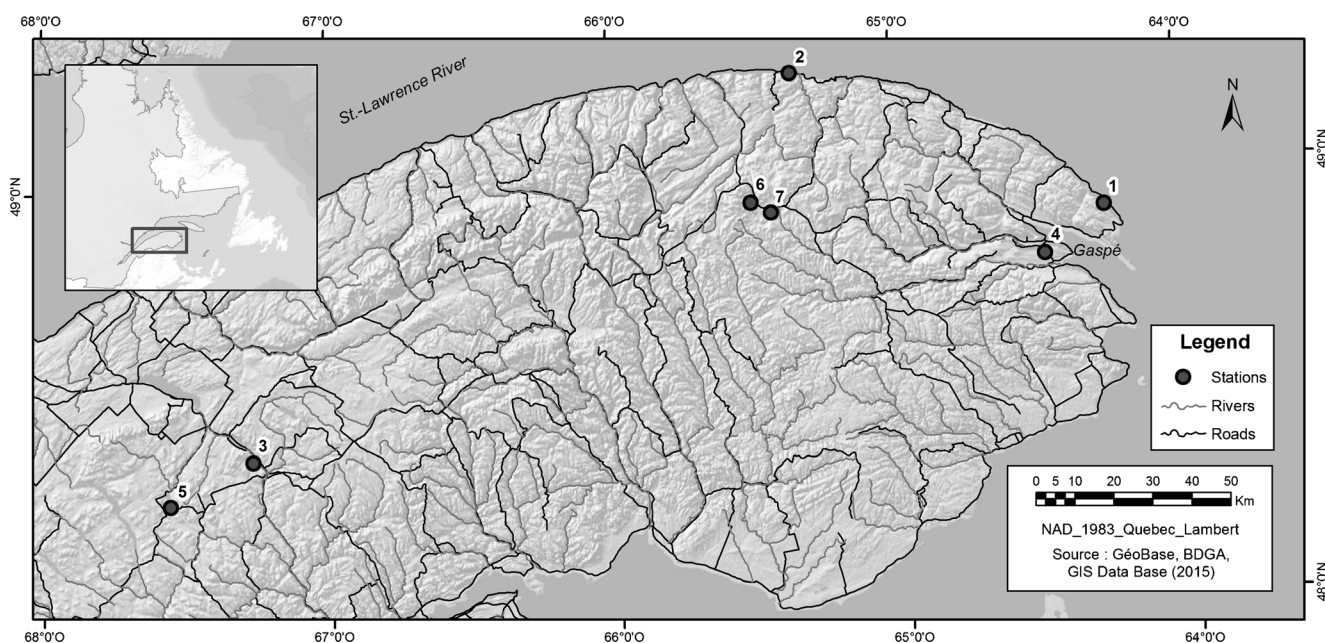


Fig. 1 Location of the weather stations used in this study. Weather stations (see Table 1 for more details) are the following: 1. Cap-des-Rosiers; 2. Cap-Madeleine; 3. Causapschal; 4. Gasp   A; 5. Lac Humqui; 6. Mont-Joli; 7. Murdochville (mapping: Gabriela Goudard)

Table 1 Weather stations in the Gaspé Peninsula used in the study

Stations	Latitude N	Longitude O	Altitude [m]	Period	Missing data (%)
Cap-des-Rosiers	48° 51' 00"	64° 12' 00"	15	1974–2013	6.5
^a Cap-Madeleine	49° 14' 00"	65° 19' 00"	2	1970–1994	6.7
^a Cap-Madeleine	49° 15' 03"	65° 19' 29"	29	1994–2013	14.3
Causapschal	48° 22' 00"	67° 14' 00"	168	1970–2013	6.7
Gaspé A	48° 46' 37"	64° 28' 41"	34.1	1970–2013	2.7
Lac Humqui	48° 17' 00"	67° 34' 00"	235.9	1972–2013	3.6
Mont-Joli	48° 36' 32"	68° 12' 27"	52.4	1970–2013	0.0
^a Murdochville	48° 57' 00"	65° 31' 00"	547.5	1970–1995	5.0
^a Murdochville	48° 57' 00"	65° 30' 00"	529	1996–2013	1.8

^aRelocation of the station

Missing data were extrapolated using the method presented in detail by Laborde and Mouhous (1998) and used previously for the same study area by Fortin and Héту (2014). This method takes into account the effects of altitude, longitude, and latitude between the stations. We then tested for homogenization.

4 Methods

4.1 Homogenization

Two distinct methods of homogenization were used on the time series of daily maximum and minimum temperatures (RHtestV4 and SPLIDHOM) to verify whether the choice of method impacts (introduce bias) the calculation of climate indices.

The first method involves the software package RHtestsV4 (Wang and Feng 2013) to detect and adjust the breaks (shifts or change-points) found in the time series. It is based on the penalized maximal *t* and *F* tests (Wang et al. 2007; Wang 2008a), which are embedded in a recursive testing algorithm (Wang 2008b). To calculate the correction factors RHtestsV4 are enriched with quantile-matching (QM). The extension includes a provision of quantile-matching (QM) adjustments (Wang et al. 2010) and the possibility to use all or some of the segments before and after a shift to estimate the QM-adjustments. We used a homogeneous reference series to

conduct data homogenization. The reference series was created by a cluster analysis based on the correlation matrix (Table 2) that allows us to group the stations on the similarity of their data regimes, the first approximation to a climatic classification of the stations (CLIMATOL-Guijarro 2011).

The second method, SPLIne Daily HOMogenization (SPLIDHOM, Mestre et al. 2011), was used to homogenized our daily data sets. This method is able to adjust the mean of the series as well as high-order moments of the series. It relies on an indirect nonlinear regression method, where the estimation of the regression functions is performed by cubic smoothing splines. To apply this method, it is necessary to have a well-correlated reference series. The reference series does not necessarily need to be entirely homogeneous but should be homogeneous on subperiods around each break affecting the candidate series. Furthermore, it is necessary to know the location of the breaks in the candidate series. So to highlight the unknown breaks, we used HOMER (HOMogenization softwarE in R) (Acquaotta et al. 2016; Mestre et al. 2013), a recently developed method for homogenizing monthly and annual temperature and precipitation data. It includes the best features of some other state-of-the-art methods (COST Action ES0601, Venema et al. 2012). In HOMER, a candidate series is compared to its neighbors in the same climatic area by computing series of differences. These difference series are then tested for discontinuities. Without metadata, the detected changes in the resulting difference series might have been caused by the candidate or by the neighbor. But if a detected

Table 2 Neighbor stations selected by cluster analysis for maximum temperature (TX) and minimum temperature (TN)

Stations	TX	TN
Cap-des-Rosiers	Cap-Madeleine-Gaspé	Gaspé-Mont-Joli
Cap-Madeleine	Gaspé-Cap-des-Rosiers	Murdochville-Mont-Joli
Causapschal	Lac Humqui-Mont-Joli-Cap-Madeleine	Lac Humqui-Mont-Joli
Gaspé	Cap-des-Rosiers-Cap-Madeleine	Cap-des-Rosiers-Causapschal
Lac Humqui	Causapschal-Mont-Joli-Murdochville	Causapschal-Mont-Joli
Mont-Joli	Lac Humqui-Murdochville-Cap-Madeleine	Murdochville-Cap-Madeleine
Murdochville	Lac Humqui-Mont-Joli-Causapschal	Cap-Madeleine-Mont-Joli

change-point remains constant throughout the set of comparisons of a candidate station with its neighbors, it can be attributed to this candidate station (Mestre et al. 2013). HOMER detected a number of change-points in the minimum and maximum temperature series that seem to be non-climatic (Table 3). The metadata allow us to explain change as it occurs because of the relocation of stations in 1994 (Cap-Madeleine) and 1995 (Murdochville and Gaspé for the TN). However, other change-points were observed for TN in 1983, 1984, 1988, and 2004; for TX in 2001, 2002, 2004, and 2005; and in 1979 for both TX and TN (Lac Humqui station).

Moreover, in some cases, it might be possible to skip the homogenization by using homogenized data sets provided by various institutions. In the present case, the Adjusted and Homogenized Canadian Climate Data are available online for 338 Canadian stations (Vincent et al., 2012; Environment Canada, 2016b). We decided, however, to use the raw data and to perform the homogenization procedure ourselves because only three of the seven stations are available from this database. This ensures that all the stations provide data that is comparable using the same procedures.

On the new homogenized series, we have calculated the climate indices with ClimPACT software and compared the results (Fig. 2).

4.2 Temperature indices and trends

The World Meteorological Organization, through the Climate Variability and Predictability (WMO/CLIVAR) Expert Team on Climate Change Detection, Monitoring Indices (ETCCDMI), has organized workshops to bring researchers together to discuss and improved data quality control and climate index calculations. The main principle behind the calculation of climate indices consists in using thresholds to characterize the frequency, intensity and duration of extremes based on daily time series of precipitation and temperatures (Karl et al. 1999). Based on the 27 climate indices whose use is encouraged by ETCCDMI, Zhang and Yang (2004) have

developed RClimDex, a software package for the calculation of climate extreme indices for monitoring and detecting climate change. This software has been modified to create ClimPACT a similar R software package that can also be used for climate indices calculation. This is the software that was used for this study. Table 4 present the indices that have been chosen for our study area.

To compare the results between the two homogenization methods, an accurate statistical analysis was carried out on ten climate indices, SU, ID, TX10p, WSDI, TX90p, FD, TN10p, CSDI, TN90p, and DTR (Table 4), calculated by the two homogenization methods. To evaluate the homogeneity of the variance of the annual data, the nonparametric Fligner-Killeen test was applied (Conover et al. 1981). The variance analysis allowed us to compare the internal variability of the two data series and to evaluate whether their differences are only due to the chance alone.

To compare the mean of the indices, an Honest Significant Difference Tukey test, HSDTukey, was carried out. The test is a single-step multiple-comparison procedure data, used to find means that are significantly different from each other (Yandell, 1997; Miller, 1981). A $p = 5\%$ significance level was used for all tests. For all weather stations scatter plots and box plots with the results of the indices were created (Fig. 3). In general, the results show that most of the climate indices present the same statistical features. In only a few cases did the tests highlight significant differences (Table 5). For the DTR index for Cap-des-Rosiers, Causapsal, Gaspé, Cap-Madeleine, and Mont-Joli, the tests show differences in the variance and in the mean between the two series created with RHtestsV4 and SPLIDHOM. The same situations occurs with the SU index in three locations, Causapsal, Lac Humqui and Murdochville. This comparison suggests the DTR and SU indices are influenced by the homogenization test chosen.

The differences identified by the two tests are well represented in Fig. 3, where the scatter plots and box plots of two indices, DTR and TX_{90p}, for Cap-des-Rosiers are presented. The DTR index presented statistical significant differences in the mean and in the variance of two series while the TX_{90p} index shows a good continuity between the two series. In this last case, the comparison analysis has not shown statistically significant differences, confidence interval 95 %, and the two series presented the same means and variances, and consequently, the index presents the same behavior (Fig. 3, down).

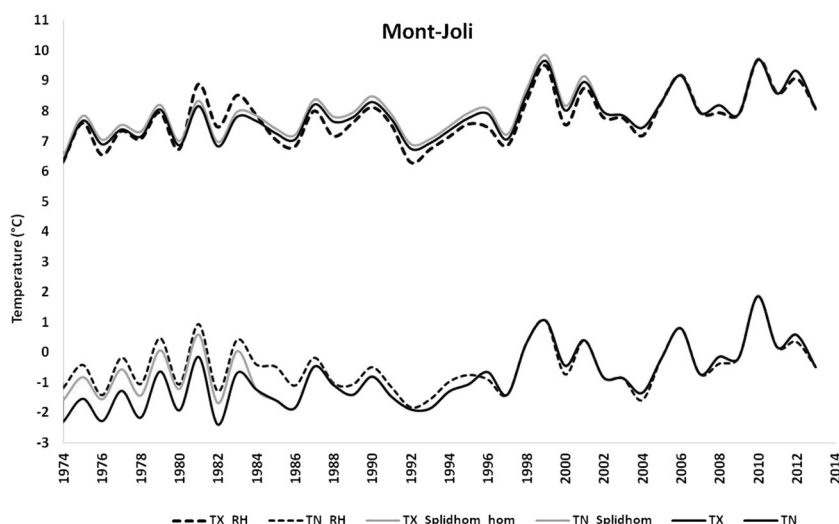
To detect and estimate trends in our time series over the entire period, we used two nonparametric tests: the Mann-Kendall for the trend detection (Mann 1945; Kendall 1975) and Sen's method (an estimator of slope) for the magnitude of the trend (Sen 1968). We also generated a regional index (RI) for each of the indices, which is the mean value for all the stations. The trend was also calculated for the RI to give us a better idea of the main trend for the entire study area. If most of the stations showed the same trend, it should also be

Table 3 Change-points identified by HOMER for maximum (TX) and minimum (TN) average monthly temperatures

Stations	TX	TN
Cap-des-Rosiers	2002	2004 and 1988
Cap-Madeleine	1994 ^a	1994 ^a
Causapsal	None	1984
Gaspé	2002	1995
Lac Humqui	2005 and 1979	1979
Mont-Joli	2001	1983
Murdochville	2004 and 1995 ^a	1995 ^a

^a These two stations were relocated during this period

Fig. 2 Annual mean of daily minimum and maximum temperatures for Mont-Joli before (black line) and after (dashed line with RHtestsV4 and gray line SPLIDHOM test) adjustment for observation time



observed in the RI. However, the RI results are an average value of the seven stations and need to be used with care.

5 Results and discussion

We calculated the trends with both homogenization methods but decided to report only the results derived from the RHtestsV4 in this article. This homogenization test is the better method when you have a very few common and well-known metadata for all the time series. It is also the one most commonly used in Canada and permits a better comparison to the other series.

Some indices (SU and WSDI) showed almost no significant trends over the study period for most of the stations (Table 6). By contrast, others (ID and TX10p) clearly indicate strong negative trends for all stations. Some results are less clear; in some cases, a majority of the stations showed either positive (TX90p and CSDI five stations and the RI for four stations, also the RI for the FD index) or negative (TN10p for five stations and

the RI) trends, while in other instances, some stations are showing divergence in the trends, but this is only the case for the DTR index where the values are significant (for five stations) but they remain low with either a slight positive (Cap-Madeleine, Gaspé, and Mont-Joli) or negative (Cap-des-Rosiers and Lac Humqui) trend.

Significance level: ***: 0.1 %; **: 1 %; *: 5 %; +: 10 %. Sen's slope estimate = Q.

The RI indicates significant trends for all indices except SU and DTR (Fig. 4). These graphs show a general decrease in cold events either days (ID, TX10p, FD) or nights (TN10p). They also show an increase in warm events during days (TX90p), nights (TN90p), and both (WSDI). Over the entire 40-year period the changes are surprisingly large. For example, the number of ice days (ID) decreased by approximately 17.6 days (-0.441 days/year). While the number of cool days (TX10p) decreased by only about 7 days (-0.177 days/year), the number of frost days (FD; -0.357 days/year) and the cold spell duration indicator (CDSI; -0.335 days/year) dropped by almost 14 days.

Table 4 Definitions of temperature indices. TX and TN are daily maximum and minimum temperature, respectively

Element	Index	Indicator name	Definitions	Units
TX	SU	Summer days	Annual count when TX (daily maximum) >25 °C	Days
	ID	Ice days	Annual count when TX (daily maximum) <0 °C	Days
	TX10p	Cool days	Percentage of days when TX <10th percentile	%
	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX >90th percentile	Days
	TX90p	Warm days	Percentage of days when TX >90th percentile	%
TN	FD	Frost days	Annual count when TN (daily minimum) <0 °C	Days
	TN10p	Cool nights	Percentage of days when TN <10th percentile	%
	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN <10th percentile	Days
	TN90p	Warm nights	Percentage of days when TN >90th percentile	%
Both	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C

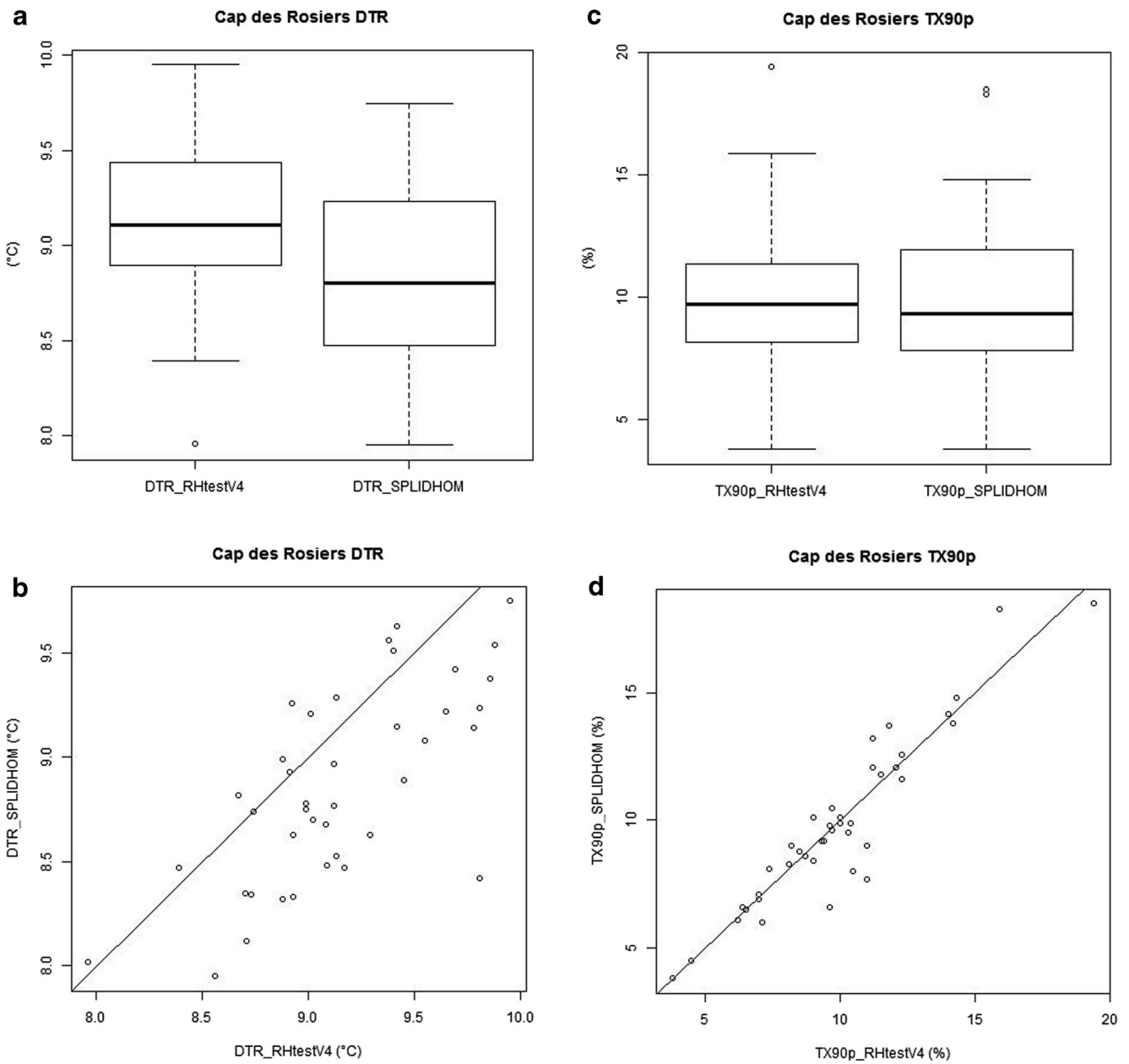


Fig. 3 The box plot and the scatter plot for the DTR, *top*, and for Tx_90p, *down*, for Cap-des-Rosiers station

Table 5 The results of comparison between the climate indices with RHtestsV4 and SPLIDHOM methods. 1: the tests do not show a statistical difference between the two series. 2: the tests highlighted statistical differences for the variance and the mean between the two series

	TX_10p	TX_90p	TN_10p	TN_90p	SU	ID	WSDI	FD	CSDI	DTR
Cap-des-Rosiers	1	1	1	1	1	1	1	1	1	2
Causapscal	1	1	1	1	2	1	1	1	1	2
Gaspé	1	1	1	1	1	1	1	1	1	2
Lac Humqui	1	1	1	1	2	1	1	1	1	1
Cap-Madeleine	1	1	1	1	1	1	1	2	1	2
Mont-Joli	1	1	1	1	1	1	1	1	1	2
Murdochville	1	1	1	1	2	1	1	1	1	1

Table 6 Annual trends for temperature indices, 1974–2014 (calculated from homogenized data with RHtestsV4)

Indices/stations	SU	ID	TX10p	WSDI	TX90p	TN90p	FD	TN10p	CSDI	DTR
Cap-des-Rosiers	0	-0.356 +	-0.089 *	0.098	0.044	0.311 ***	-0.582 ***	-0.070	-0.391 **	-0.015 **
Cap-Madeleine	0 *	-0.500 **	-0.213 ***	0.455 **	0.173 ***	0.023	-0.048	-0.102 ***	-0.099	0.025 ***
Causapsal	-0.103	-0.368 *	-0.191 ***	0.135	0.084 +	0.159 ***	-0.596 **	-0.172 **	-0.380 **	-0.009
Gaspé	0.164	-0.500 **	-0.184 ***	0.333 *	0.104 *	0.061	0	-0.074	-0.169	0.022 *
Lac Humqui	0	-0.375 *	-0.157 **	0.053	0.047	0.110 **	-0.500 **	-0.125 ***	-0.317 **	-0.018 **
Mont-Joli	0.062	-0.474 **	-0.209 ***	0.183	0.083 *	0.022	-0.167	-0.144 ***	-0.400 *	0.018 ***
Murdochville	-0.071	-0.460 **	-0.213 ***	0.179	0.076 *	0.124 **	-0.500 ***	-0.226 *	-0.641 ***	-0.009
Regional index	0.027	-0.441 **	-0.177 ***	0.199 +	0.088 *	0.110 **	-0.357 **	-0.130 ***	-0.335 **	0.001

Significance level: *** : 0.1%; **: 1%; *: 5%; +: 10%. Sen's slope estimate = Q

Overall, the results show a warming of the surface air temperature for most of our stations. The frequency of warm days (TX90p) and warm nights (TN90p) increased, while the frequency of ice days (ID), cool days (TX10p), and cool nights (TN10p) declined. These results are in agreement with the main conclusions of the IPCC (2012, 2013) which stated that is very likely that the number of cold days and nights has decreased, while the number of warm days and nights has increased on the global scale since 1950. However, changes in precipitation indices are less consistent and the trends for Gaspé are generally weak (Fortin and Héту 2014). Mékis and Vincent (2011) have found that total rainfall amounts have increased by 5 to 10 % in southern Canada over the last century, while snowfall trends were larger and more variable throughout the country. For southeastern areas, there is a mix of increasing and decreasing trends of annual snowfall, and it is therefore unclear whether the trends have significantly changed over our study area. But at the global scale, extreme precipitation is expected to increase with warming along IPCC (2013), and this is what we would expect for the Gaspé Peninsula. In the northeastern USA, in the mountainous area around Mount Washington, (Seidel et al. 2009) found evidence of an increase in air temperature, which has had a significant impact on snowpack. By contrast, in recent years, the snowpack in the Gaspé Peninsula had not been significantly affected by climate warming (Fortin and Héту 2012, 2014), although if warm temperatures increase while the cold temperatures decrease, the situation could change (Henderson and Muller, 1997). For example, Fortin (2010) observed an increase in freeze-thaw cycles in the region of Quebec City starting in the late 1970s, and this trend should continue over the next decades. In Gaspé, if such warming occurs during wintertime, this could eventually increase rain on snow events, modifying river flow and increasing occurrences of some kinds of natural hazards like wet snow avalanches and slushflows (Fortin and Héту, 2012,

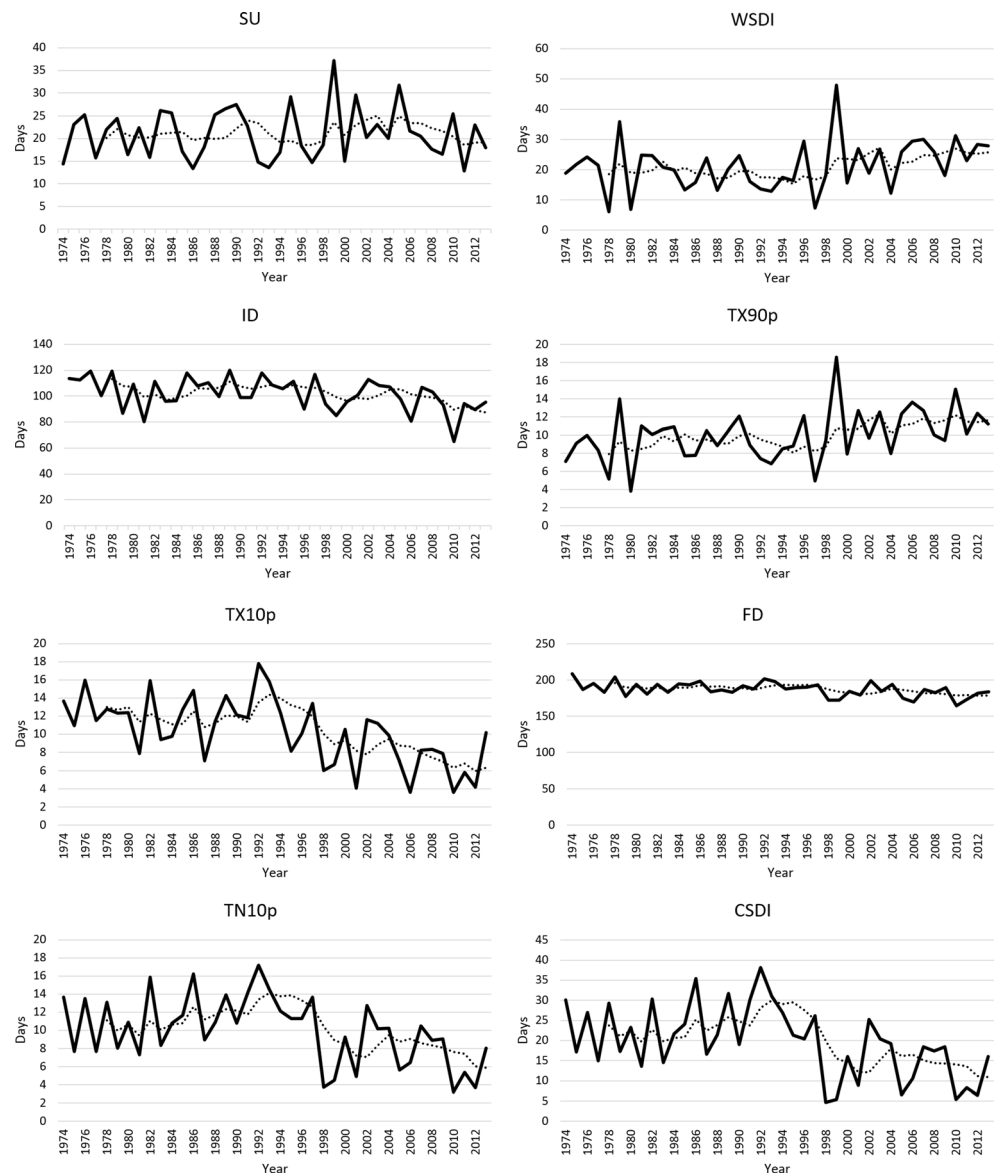
2014; Fortin et al., 2015). This kind of climate shift could have adverse impacts on hydrology, ecology, health (Dore 2003; Greenough et al. 2001; Kunkel et al. 1999; Parmesan et al. 2000; Rosenzweig et al. 2001), agriculture, and transportation infrastructures (Fortin, 2010). In fact, territories like the Gaspé peninsula have both glacial and periglacial environments (Giaccone et al. 2015; Gray and Brown, 1979; Héту and Gray, 2000) which are currently susceptible to significant transformations, and the analysis of temperature indices is important to understand the future evolution of this landscape, under climate change effects (Acquaotta et al. 2015; Beniston 2003; Comou and Rahmstorf 2012; Fratianni et al. 2015; Mouhame et al. 2013; Peterson and Manton 2008; Retchless et al. 2014; Smith and Lawson 2012; Spinoni et al. 2015; Terzago et al. 2013; Trenberth 2012).

6 Conclusions

Access to data of sufficient quality is a major issue in climate studies. In recent years, several methods have been developed to address this issue by proposing statistical approaches to improve data control. In this study, we used SPLIDHOM, HOMER, and RHtestsV4 for data homogenization to ensure the quality of data before we used them to calculate a number of thermal indices with ClimPACT.

Several thermal indices demonstrate that throughout the Gaspé Peninsula recent warming affected the area primarily by increasing the number of warm nights and days and by reducing the number of cold nights and days. Some discrepancies were observed in the indices for various weather stations. For example, ice days (ID) and cool days (TX10p) exhibit strong negative trends for all stations while other indices like summer days (SU) and the warm spell duration indicator (WSDI) revealed few significant trends over the study period. At this point, it is

Fig. 4 Regional index (see Table 2 for each index description). The *dotted line* is the 5-year moving mean (using the homogenized data with RHtestsV4)



not clear if a specific area in the Gaspé Peninsula is more or less affected than others, and this is partly due to the limited number of weather stations available in the study area. In addition, caution should be used in the interpretation of our results since each statistical method has its inherent biases and potential errors. Our results reveal the necessity of taking into account the potential changes in extreme thermal events and their impacts on the ecosystem, including disturbances of the phenology stages and the hydrological cycle.

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