A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis

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Received 28 March 2012; revised 8 August 2012; accepted 9 August 2012; published 22 September 2012.

[1] This study presents a second generation of homogenized monthly mean surface air temperature data set for Canadian climate trend analysis. Monthly means of daily maximum and of daily minimum temperatures were examined at 338 Canadian locations. Data from co-located observing sites were sometimes combined to create longer time series for use in trend analysis. Time series of observations were then adjusted to account for nation-wide change in observing time in July 1961, affecting daily minimum temperatures recorded at 120 synoptic stations; these were adjusted using hourly temperatures at the same sites. Next, homogeneity testing was performed to detect and adjust for other discontinuities. Two techniques were used to detect non-climatic shifts in de-seasonalized monthly mean temperatures: a multiple linear regression based test and a penalized maximal t test. These discontinuities were adjusted using a recently developed quantile-matching algorithm: the adjustments were estimated with the use of a reference series. Based on this new homogenized temperature data set, annual and seasonal temperature trends were estimated for Canada for 1950–2010 and Southern Canada for 1900–2010. Overall, temperature has increased at most locations. For 1950–2010, the annual mean temperature averaged over the country shows a positive trend of 1.5°C for the past 61 years. This warming is slightly more pronounced in the minimum temperature than in the maximum temperature; seasonally, the greatest warming occurs in winter and spring. The results are similar for Southern Canada although the warming is considerably greater in the minimum temperature compared to the maximum temperature over the period 1900–2010.

Citation: Vincent, L. A., X. L. Wang, E. J. Milewska, H. Wan, F. Yang, and V. Swail (2012), A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis, *J. Geophys. Res.*, *117*, D18110, doi:10.1029/2012JD017859.

1. Introduction

[2] The development of high-quality surface air temperature data sets has received considerable attention in recent years due to the rising interest in understanding and quantifying how our climate is changing. Long-term time series of reliable temperature data at fine time and spatial resolution are required for a better assessment of climate variability and change on local and regional scale, as well as changes in extremes. High-quality temperatures data are also needed in near real-time to monitor the effects of climate change and extreme events on today's society.

[3] Original temperature records are not always suitable for proper analysis of climate change. Non-climatic variations (inhomogeneities) are often present in temperature series due to changes in instrumentation, in local site condition and environment, in observing practices and observing time, as well as site relocation and station automation, etc. (these are among the main factors leading to inhomogeneities in temperature records [*Trewin*, 2010]). Inhomogeneities can seriously interfere with the proper assessment of any climate trends and extremes. For this reason, testing and adjusting (if necessary) temperature time series have become an essential component of climate analysis.

[4] A large number of techniques have been developed for detection of inhomogeneities in temperature series: see *Venema et al.* [2012], *Aguilar et al.* [2003] and *Peterson et al.* [1998] for detailed reviews. Many of these techniques were applied to original temperature data time series in order to homogenize them. Trend analysis using homogenized temperatures was carried out in Australia [*Della-Marta et al.*, 2004], China [*Li et al.*, 2009], Finland and the North Atlantic countries [*Tuomenvirta*, 2001], Switzerland [*Begert et al.*, 2005], Spain [*Brunet et al.*, 2006], the United States [*Menne et al.*, 2009], and Canada [*Vincent and Gullett*, 1999], to name a few. Many homogenized data sets were also included

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in the global temperature data sets to obtain an estimate of temperature averages at global scale [*Jones et al.*, 2012]. A few studies have compared the ability of various techniques for detecting inhomogeneities in temperature series [*Ducré-Robitaille et al.*, 2003; *DeGaetano*, 2006; *Reeves et al.*, 2007; *Domonkos*, 2011]. The large number of different techniques and the need for a realistic comparative study has led to a coordinated European initiative, the COST Action Advances in Homogenization Methods of Climate Series [*Venema et al.*, 2012; *Action COST ES0601*, 2011]. Most techniques were developed to homogenize annual and monthly mean temperatures in order to produce long-term homogeneous series to improve estimates of trends and variability.

[5] In the mid-1990s, a first generation of homogenized temperature data sets was prepared for the analysis of climate trends in Canada [*Vincent and Gullett*, 1999]. Non-climatic shifts due to station relocation and change in observing time were identified in the annual means of daily maximum and minimum temperatures using a technique based on regression models and neighboring stations [*Vincent*, 1998]. Monthly adjustments were obtained from fitting regression models to monthly mean data series for each calendar month separately and applied to bring each homogeneous segment into agreement with the most recent homogeneous part of the series. For each non-climatic shift, the 12 monthly adjustments were later interpolated to each calendar day to derive daily adjustments, which were applied to produce the first generation of homogenized daily maximum and minimum temperatures [*Vincent et al.*, 2002]. Homogenized data sets were prepared for 210 locations across the country. Co-located station observations were sometimes joined in time to produce a longer time series. These homogenized temperatures were used in many studies including the analysis of trends in annual and seasonal temperature and precipitation in Canada [*Zhang et al.*, 2000], changes in temperature and precipitation daily indices [*Vincent and Mekis*, 2006], hemispheric and global assessment of temperature averages [*Jones and Moberg*, 2003], and global assessment of extreme temperature and precipitation changes [*Alexander et al.*, 2006].

[6] In this study, a second generation of homogenized monthly mean temperature data sets is developed with a number of improvements. First, the station list was revised to include more stations, offering a better spatial and temporal coverage. Second, a new adjustment method was applied to the daily minimum temperatures of 120 stations in order to resolve the bias caused by the change in observing time in 1961. Third, although the first generation of homogenized temperature data sets were updated every year with the most current data, homogeneity testing and adjustments have been done thoroughly only twice, in mid-1990s and early 2000s. Therefore, there was an urgent need to re-test the full period at each station and to adjust the data accordingly if necessary; in this study, a couple of techniques for detecting non-climatic shifts were used in an attempt to obtain the best possible results. Finally, a newly developed quantile-matching (QM) adjustment algorithm was applied to adjust for the identified non-climatic shifts in monthly mean temperature series.

[7] The primary objective of this study is to document all procedures used to produce the second generation of homogenized monthly mean temperature data sets. Proper documentation is crucial for assisting users to comprehend any limitations of the data sets and to ensure a proper interpretation of the results derived from the data sets. A second objective is to present an updated analysis of the annual and seasonal temperature trends in Canada using the newly homogenized data sets which cover a longer period of time (to 2010) and have an improved spatial coverage.

[8] The rest of this paper is organized as follows. Section 2 describes the data and methodologies, and in particular joining of observations from co-located stations, adjustments of daily minimum temperatures for the change in observing time in 1961, detection and adjustment of non-climatic shifts in monthly data series. Section 3 presents the estimated trends in annual and seasonal means of the daily maximum, minimum and mean temperatures for Canada for 1950–2010 and Southern Canada for 1900–2010. A discussion is provided in section 4 and a few concluding remarks are given in section 5.

2. Data and Methodologies

2.1. Data

[9] Daily maximum and minimum temperatures were directly retrieved from the National Climate Data Archive of Environment Canada. The station selection was based on data quality, longevity, spatial and temporal coverage, including counts of missing values. Homogenized data sets were produced for 338 locations (Figure 1). Most of these stations are the same as those in the first generation, except that 10 stations had to be removed due to their proximity to other selected sites or count of missing values. Some viable stations from the second generation of adjusted precipitation data set [*Mekis and Vincent*, 2011] were included in this new version to provide both daily temperature and precipitation at as many common locations as possible. Figure 1 shows that the newly added stations improve spatial coverage, mainly in the south (only nine stations were added north of 60°N). Temporal coverage is also improved since many of the added stations have long records in the past (Figure 1). The main goal of the first generation data set was to analyze the trends for the century 1895–1995. In the second generation, the entire record of each station is used, including 19 stations with data starting in the 1870s and one station (Toronto) with daily temperatures from 1840 to the present.

2.2. Joining of Co-located Stations Observations

[10] The climate observing network in Canada has considerably changed over its long period of taking climate observations, especially since 1990 due to the downsizing of the traditional network and the increased use of automated systems. For this reason, station closures and relocations are two major and ongoing issues in Canada. A new station identification number is often given to the new station when it opens or is relocated (station relocations can also occur without a change in identification number). In order to have long time series useful for trends analysis, it was often necessary to merge observations at co-located stations, which were usually no more than 20 km apart. This was done for 63% of the stations (213 locations) in the second generation data sets. Sometimes, the observations of three or four stations were joined to form a long series. Overall, 43% of the stations have one joining date, and 16% and 4% of the stations have two and three joining dates, respectively.

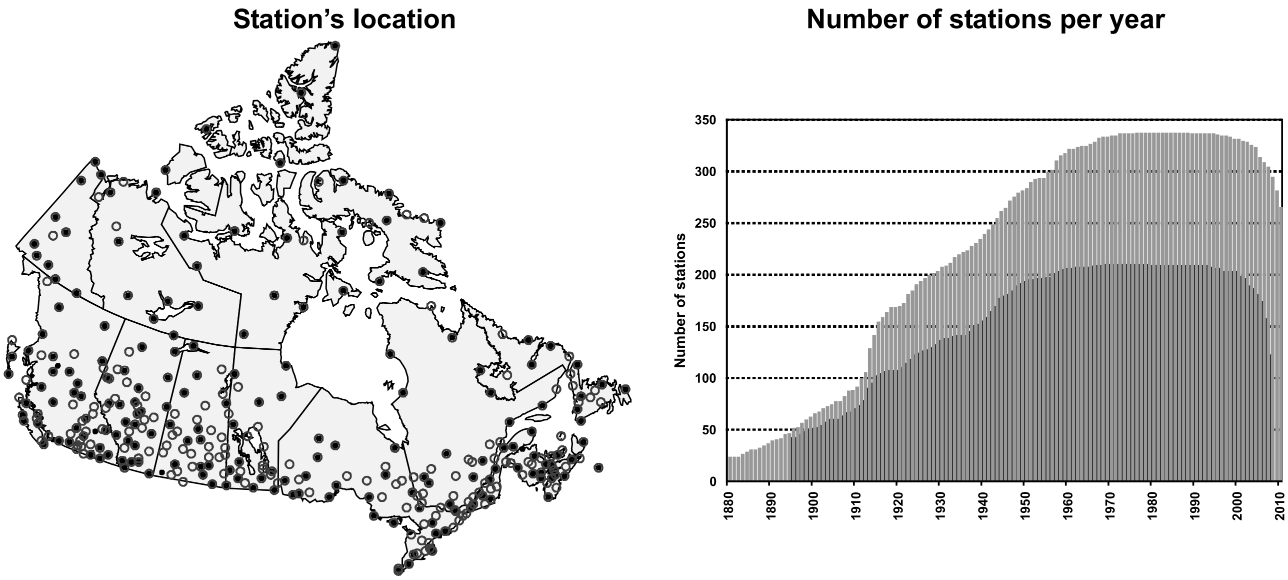

Figure 1. Location of the second generation's 338 stations (circles) and first generation's 210 stations (dots). Number of stations in the second generation (gray) and first generation (black) reporting per year.

[11] Figure 2 shows the number of joining dates per year. A first peak is observed in 1942/1943: these joining dates generally correspond to rural observing sites (located at houses or farms) that were closed while the instruments were relocated to nearby newly built airport stations. The second peak in 1965/1966 does not have any particular documented cause. The third peak around 1994/1995/1996 is largely due to stations that have fully or partially ceased human observations: these sites were often closed and then re-opened with automated observing systems. The last peaks of 2005 and 2008 are not necessary associated with station closures but mainly to the introduction of a new practice regarding the quality assurance/control (QA/QC) applied to daily climate data. To ensure continuity of daily temperature time series in the recent years, for the second generation data sets, it was sometimes necessary to merge data that have received a complete set of routine QA/QC procedures in the past with newer data that have received minimal or no QC in the archives. Because of this, for the purpose of this study, a few basic checks had to be applied to ensure that the data extracted from the archives was reasonable. Daily temperatures below −60°C and above 50°C were identified and compared to neighbors: data value was retained or set to missing. Long sequences of consecutive zero values at a few automatic sites were as well identified and set to missing.

2.3. Correction of the Bias in Daily Minimum Temperatures Caused by the Change in Observing Time in 1961

[12] During the preparation of the first generation of homogenized temperature data sets [*Vincent and Gullett*, 1999], a decreasing shift in 1961 of about 0.6 to 0.8°C on average was identified in the annual mean of the daily minimum temperatures at many synoptic stations (mainly airports). This "bias" was found to have resulted from a nation-wide change in observing time on 1 July 1961 at synoptic stations. In 1961, it was decided to change the reporting time of the daily minimum temperature from the 24-h observing window ending at 0000 UTC (coordinated universal time) to the window ending at 0600 UTC. Since the 0600 UTC hour corresponds more closely to the time when the actual daily minimum temperature occurs, particularly in eastern Canada, it was more likely that the same minimum (or a similar minimum) temperature was recorded on two successive calendar days, consequently introducing a cold bias in the annual and monthly means of daily minimum temperatures. For maximum temperature, the observing window was changed from 1200 UTC to 0600 UTC in July 1961: the effect of this change on daily maximum temperature was considered to be negligible [*Vincent et al.*, 2009; *Cameron and Wilson*, 1996]. In a separate study involving many observing stations across Canada, *Hopkinson et al.* [2011] quantified that this change for maximum temperature affected much fewer stations than in the case of minimum temperature and the magnitude of the difference between observing windows was also much smaller.

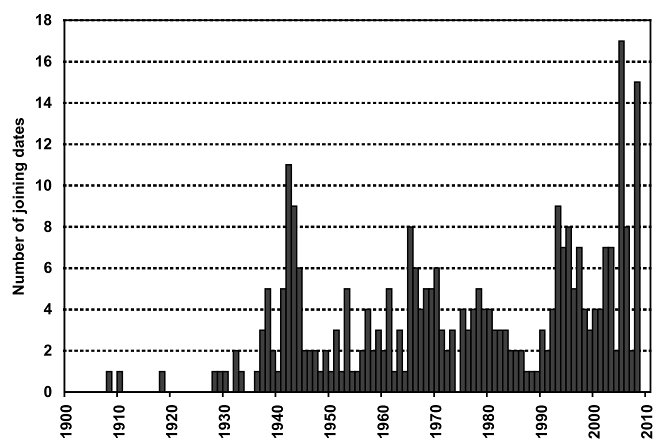

Figure 2. Number of joining dates per year (for the second generation data set).

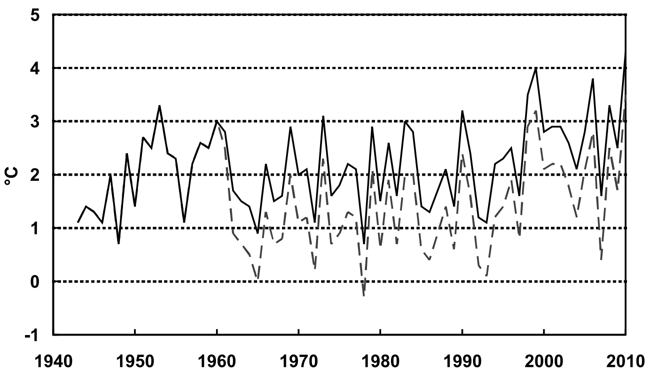

Figure 3. Annual mean of the daily minimum temperatures for Greenwood, Nova Scotia, before (gray – dashed line) and after (black – solid line) adjustments for observation time change in 1961.

[13] During the preparation of the first generation data set, the adjustments were performed in the following way. Since the most recent period (since 1961) was affected, monthly adjustments derived from regression models were applied to bring the monthly data for the period since 1961 into agreement with the second most recent homogeneous part of the series (before 1961). Later, adjustments were also applied to all daily values by interpolating the monthly adjustments to each calendar day of year [*Vincent et al.*, 2002]. At that time, these adjustments were considered to be sufficient for the purpose of preserving consistency between adjusted daily data and homogeneous monthly data time series, while further investigation of this bias was deemed necessary.

[14] Recently, the cold bias in the minimum temperatures was further investigated by *Vincent et al.* [2009]. They found that not all days were affected by the change in observing window in 1961: the annual percentage of affected days ranged from 15% for locations in the west to 38% for locations in the east. Further, they developed a procedure that uses hourly temperature observations to adjust daily minimum temperatures. This procedure includes the following steps. First, an affected day is detected when the lowest hourly temperature in the 24-h window ending at 0600 UTC is colder than the lowest hourly temperature in the 24-h window ending at 0000 UTC. Then, for this particular day, the daily minimum is estimated to be 0.5°C lower than the lowest hourly temperature in the 24-h window ending at 0000 UTC (the subtraction of 0.5°C is to remove the small difference between the true daily minimum and the lowest hourly temperature; see *Vincent et al.* [2009] for more details).

[15] In the current study, the approach developed by *Vincent et al.* [2009] was applied to correct the cold bias in daily minimum temperatures recorded at 120 synoptic stations over the period since 1961. Adjusting the period prior 1961 (instead of after 1961) would have resolved the decreasing step detected in the monthly time series, but it would also have created "incorrect" daily minimum temperatures before 1961 that do not correspond to actual minimums in the daily temperature cycle. In addition, adjusting minimum temperatures after 1961 has preserved consistency between synoptic and volunteer stations [*Hopkinson et al.*, 2011]. An example of the impact of this correction on annual values is provided for the station Greenwood, Nova Scotia. As shown in Figure 3, the time series shows warmer annual temperatures after the correction, which consequently affects the overall trend. In the future, when updating the second generation data sets, the same procedure will be applied to correct daily minimum temperatures of the most current year.

2.4. Detection of Non-climatic Shifts in Monthly Series

[16] In this study, two techniques were applied to detect non-climatic shifts in monthly mean temperature time series: the multiple linear regressions (MLR) based test [*Vincent*, 1998] that was used for the first generation of homogenized temperatures, and a penalized maximal t (PMT) test based algorithm [*Wang et al.*, 2007; *Wang*, 2008]. Other studies have also used multiple tests for detection of non-climatic shifts in temperature time series [*Menne and Williams*, 2005; *Wijngaard et al.*, 2003]. Although inhomogeneities may take the form of change in mean or in variance, or in both, the focus here is to detect changes in the mean (simply referred to as shifts hereafter). Both techniques were applied using the same reference series.

[17] The MLR test [*Vincent*, 1998] with two regression models for the detection of shifts was applied in this study; the other two models for the detection of trends [*Vincent*, 1998] were not used. The dependent variable was the candidate series (tested series) while the independent variable was the reference series (neighbor series). An additional independent variable was added to the model to describe a potential shift in the candidate series. When the date k of the shift is unknown, it is necessary to find the date k that corresponds to the minimum sum of squared residuals, namely, the most probable date k for a shift. The statistical significance of the most probable shift is determined using a maximal F test statistic. When a significant shift is detected, the time series is divided at the date of the shift, and each segment (before and after the shift) is re-tested separately. The procedure was repeated until all the segments of the series were found to be homogeneous.

[18] The PMTred algorithm [*Wang*, 2008] is based on the PMT test [*Wang et al.*, 2007] for detecting unknown shifts in time series of no temporal trend. It also searches for the most probable position of shift in a segment of the series being tested and tests its statistical significance using a penalized maximal t test statistic, in which the lag-1 autocorrelation is also accounted for. Because the time series being tested is assumed to have no temporal trends, the PMTred algorithm needs to use a reference series to represent trends and low-frequency variations in the candidate series. The PMTred algorithm is applied to the time series of the differences between the candidate and reference series. Different from this, the MLR technique uses the reference series as a regression variable, so that trends and low-frequency variations are to be accounted by the regression relationship between the candidate and the reference series, to be diminished from the residual series. Other differences between the MLR and PMTred methods include: (1) PMTred accounts for the effects of unequal lengths of the two segments before and after a shift and thereby has higher detection power [*Wang et al.*, 2007]; (2) PMTred has a re-cursive testing procedure for detecting multiple changepoints in a single time series [*Wang*, 2008], and (3) PMTred accounts for lag-1 autocorrelation which are often non-negligible for climate

data time series and thereby reduces the number of false alarms [*Wang*, 2008].

[19] The MLR test is implemented using a simple FORTRAN program, with the results and time series being plotted and examined using Microsoft Excel. The PMTred algorithm is implemented using the RHtestsV3 software package [*Wang and Feng*, 2009]. This package includes plots of the relevant time series and the resulting estimates of shifts and trends in the candidate series, which are very helpful for its users. Both approaches were applied for the identification of shifts in individual candidate series. Shifts detection was performed on de-seasonalized series of monthly means of daily maximum and of daily minimum temperatures separately.

[20] Three to seven suitable neighbors were used individually as reference series. The neighbor selection was based on the proximity of the candidate station, correlation and period of data. It was possible to find relatively close and well correlated neighbors for a period of 30 to 40 years, but it was much more difficult for longer periods of time. For the second generation data set, most neighbors were within 200 km; however, they were occasionally as far as 700 km in the north. The correlation on annual values was mainly greater than 0.70 (this is in agreement with the findings of *North et al.* [2011] who have shown that correlation between annual averaged station's surface air temperature decays in a near-exponential fashion as a function of distance). When MLR and PMTred were applied using the same neighbor, the dates of the detected shifts were usually the same; but on occasion, PMTred identified additional shifts. However, the dates were sometimes very different when various neighbors were used. This could arise from inhomogeneities in some of the neighbor series (neighbor stations with known inhomogeneities were not necessary excluded depending on the date when their inhomogeneities occurred), in addition to statistical estimation error. Common shifts (identified by at least two neighbors) were retained and analyzed. The related metadata was examined for the detected shifts, along with the plots of time series and the corresponding regression fits, to determine whether the identified shifts were in the candidate series or in reference series.

[21] The homogenization process in Canada was largely based on statistical testing in order to minimize the use of the station history files [*Vincent*, 1998; *Gullett et al.*, 1991]. Such files are often retained as paper copies only: there are bulky, aged, awkward to handle physically, and the information can be sparse and incomplete. Recently, some inspector reports have been digitized, but this has been done only for a small number stations (of the 338 stations in the second generation data sets), and mainly for the most recent period of time. Still, even though incomplete, metadata is consulted whenever possible, as greater confidence is usually placed in the data adjustments if the detected shifts are supported with historical information.

[22] A detailed typical example is presented. As shown in Figure 4, shifts were detected in the monthly mean anomalies of the daily maximum temperature at Brockville, Ontario, using four neighbors. The distance between the candidate series (Brockville) and neighbor 1, 2, 3 and 4 was 54, 144, 104 and 186 km respectively; the correlation on annual values was 0.73, 0.79, 0.71 and 0.88, while the correlation on the first difference series was 0.96, 0.94, 0.95, and 0.94. The results are examined starting with the most recent changepoint. It is important to point out that all these dates except 1938 were detected by both techniques. A first changepoint was detected in 1994 with neighbor 1 and 2, and 2000 and 2001 with neighbor 3 and 4. The metadata revealed that there was a relocation of the instruments in 1994, 150 m from the old site to improve exposure. Since there was no indication of change for 2000 or 2001, 1994 was kept as the first changepoint. A second shift was identified in 1965 with neighbor 1 and 3, and in 1962 with neighbor 2 and 4. Observations from two sites were merged in 1965 (the sites were 2.6 km apart with a difference in elevation of 5 m). Although there was no indication of change in 1962 in the metadata, both 1962 and 1965 were kept as changepoints, because the shift in 1962 is visually apparent with all neighbors: it also appears to be associated with a change in variance and coincides with a data gap (in this case, it is more likely that the metadata is incomplete). The third shift in 1951 (or 1950) which was identified with neighbor 2, 3 and 4; however, we did not find any cause for this shift in the metadata. The changepoint in 1938 was detected with only one technique (PMTred) with only one neighbor and it is not supported by metadata: therefore this changepoint was not kept for adjustment. Since the neighbor 3 and 4 data series are too short to be used for identification of any shifts before 1930, the changepoint in 1928 was identified with neighbor 1 and 2 only. Although it was not supported by metadata, it is visually apparent (Figure 4) and thus was kept for adjustment. Thus, five changepoints (1994, 1965, 1962, 1951, and 1928) were retained for the Brockville series. In summary, a changepoint was generally retained when it was detected by both methods, with at least two neighbors, and preferably with metadata support.

[23] The same procedure using both techniques was used to identify shifts in the de-seasonalized monthly means of daily maximum temperatures and of daily minimum temperatures, respectively, at each of the 338 locations. The total number of detected shifts is reported in Table 1. It is important to clarify here that "no shifts" indicates that the series was found to be homogeneous: no shifts were retained for adjustment because there was no agreement among the detection results by both methods with different neighbors, and no supported metadata. About 66% (64%) of the stations have no shifts in their maximum (minimum) temperature and are considered homogeneous (thus they do not need adjustment). Sometimes shifts were identified on the same dates in both the maximum and minimum temperatures. Overall, for 190 locations both the maximum and minimum temperature series were found to be homogeneous. Table 1 also gives the causes of the shifts that are kept for adjustment. About 70% of the shifts have an identified cause including: joining of observations at co-located sites, instruments relocation (the station has kept the same identification number), and other causes such as change in observer, instruments and automation. About 30% of the shifts were adjusted although there was no metadata support (and in these cases, metadata was deemed to be incomplete, as for the 1962 shift in Figure 4). Figure 5 shows the distributions of the years of shifts identified in these series. A 1942/1943 shift occurred at 12 (10) out of the 20 joining dates for maximum (minimum) temperature; this shift was mainly due to relocation of sites to airports. A 1994/1995/1996 shift occurred in 9 (10) out of the 24

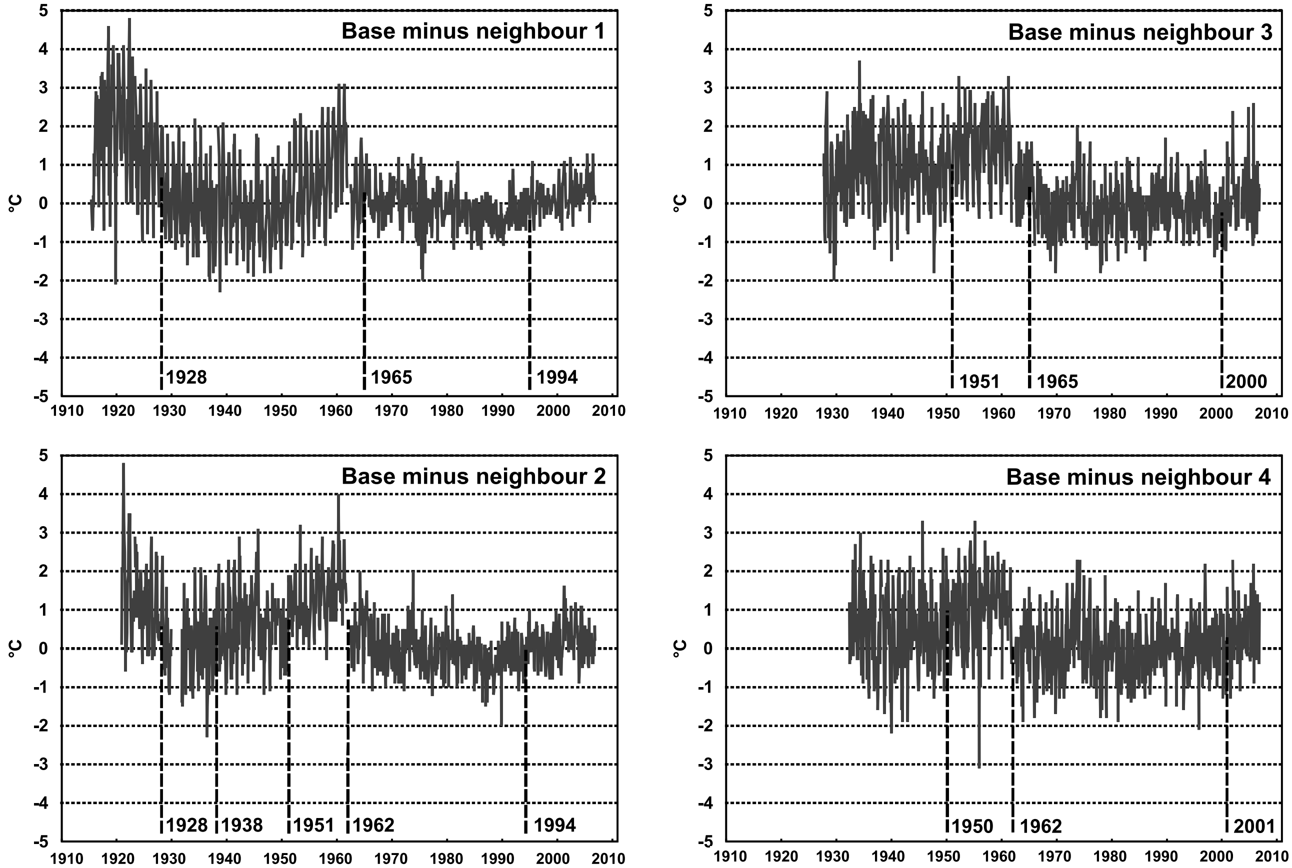

Figure 4. Difference between the monthly mean anomalies of the tested station Brockville, Ontario, and 4 neighbor stations along with the detected changepoints.

joining dates for maximum (minimum) temperature and was mostly related to automation (including relocation of the instruments).

2.5. Adjustment of Monthly Temperature for Non-climatic Shifts

[24] In the first generation data sets, a procedure based on regression models was used to obtain monthly adjustments [*Vincent et al.*, 2002] (hereafter referred as MRs for Monthly Regressions). Regression models were applied to the time series for each of the 12 individual calendar months in order to produce 12 monthly adjustments (one for each calendar month). The dependent and independent variables were the temperature of the candidate and neighbor series, respectively, and an additional independent variable was used to provide the monthly shift size when a shift is detected. For each calendar month, different estimates of the monthly shift sizes were obtained using different neighbors, and the average of these estimates was taken as the final estimate of the monthly shift size (gray bars in Figure 6a). A polynomial of degree two was then applied to the 12 monthly adjustments in order to produce 12 smoothed monthly adjustments (black line in Figure 6a). A period of 20 years before and after each shift was usually used for the regression models, however the period was sometimes shortened due to inhomogeneities in the candidate and neighbor series.

[25] In the second generation data sets, monthly adjustments were derived from a recently developed Quantile-Matching (QM) adjustment algorithm so that the empirical distributions of the monthly mean temperatures, before and after each shift, match each other [*Wang et al.*, 2010]. The procedure can be summarized as follows. Let $C_{bef,t}$ and $C_{aft,t}$ denote a segment of the candidate temperature series (up to 10 years in length) before and after the shift, respectively; and $R_{bef,t}$ and $R_{aft,t}$, the corresponding segments of the reference (a neighbor) temperature series. The $C_{bef,t}$ are first ranked and

Table 1. Number of Stations With No, One, Two, Three and Four Shifts Adjusted for Minimum And Maximum Temperature and Number of Shifts Due to Different Causes

	Maximum Temperature	Minimum Temperature
Number of stations with:		
No shift	224	218
One shift	71	73
Two shifts	31	32
Three shifts	8	12
Four shifts	4	3
Total number of stations	338	338
Number of shifts due to:		
Joining observations	72	78
Station / instruments relocation	33	33
Other causes	13	20
No corresponding metadata	55	54
Total number of shifts	173	185

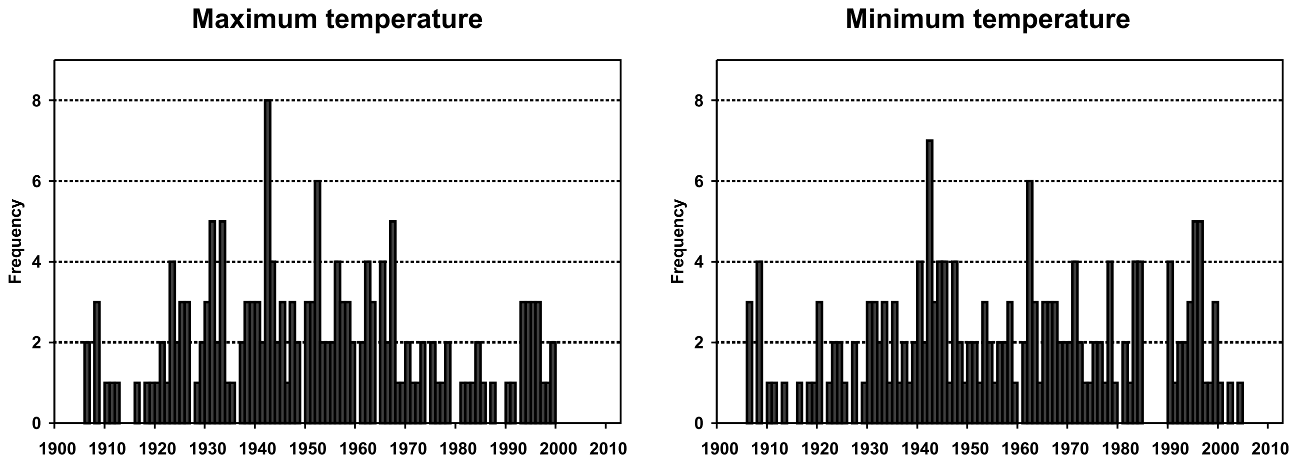

Figure 5. Frequency of the shifts identified in the series of monthly mean daily maximum temperatures (114 series/173 shifts) and daily minimum temperatures (120 series/185 shifts).

divided into M_q quantile-categories (here M_q = 12), and so are the $C_{aft,t}$. The temperature differences between the candidate and reference sites before the shift, $D_{bef,t} = C_{bef,t} - R_{bef,t}$, are binned according to the category in which $C_{bef,t}$ falls; similarly, the differences, $D_{aft,t} = C_{aft,t} - R_{aft,t}$, are binned according to the category in which $C_{aft,t}$ falls. The category-averages of the $D_{bef,t}$ ($D_{aft,t}$) are calculated for each quantile category before (after) the shift. Finally, the differences between each pair of category-averages (before and after the shift) are obtained for each category (gray bars in Figure 6b) and a natural spline is fitted to these M_q category-average differences (black line in Figure 6b). The natural spline is used to estimate QM adjustments. For example, the QM adjustment for value $C_{bef,t}$ is the value of the spline corresponding to the cumulative frequency of the value $C_{bef,t}$. Therefore, QM adjustments are usually different for temperatures of different cumulative frequencies; they might be the same if the non-climatic effect is the same across the whole distribution (a true mean shift). In this study, the reference series was provided from the best correlated neighbor having the longest homogeneous period of time surrounding the shift to be adjusted.

[26] The means of all monthly adjustments calculated from the MRs and QM procedures are very similar over an adjusted period. However, the QM adjustments have the property of being year-dependent as they differ according to where the monthly temperature value stands in the probability distribution. For example, for Brockville, the MRs procedure suggests that all January values of the homogeneous period prior 1965 be adjusted by about −0.3°C regardless if it was a cold or warm January (Figure 6a). On the other hand, the QM adjustments for the January temperatures (which fall in the lower 20-percentiles of the distribution) range from about −0.4 to −0.9°C (Figure 6b) depending if it is a warm or cold January (the QM adjustment for a warm January is different from that for a cold January). Annual

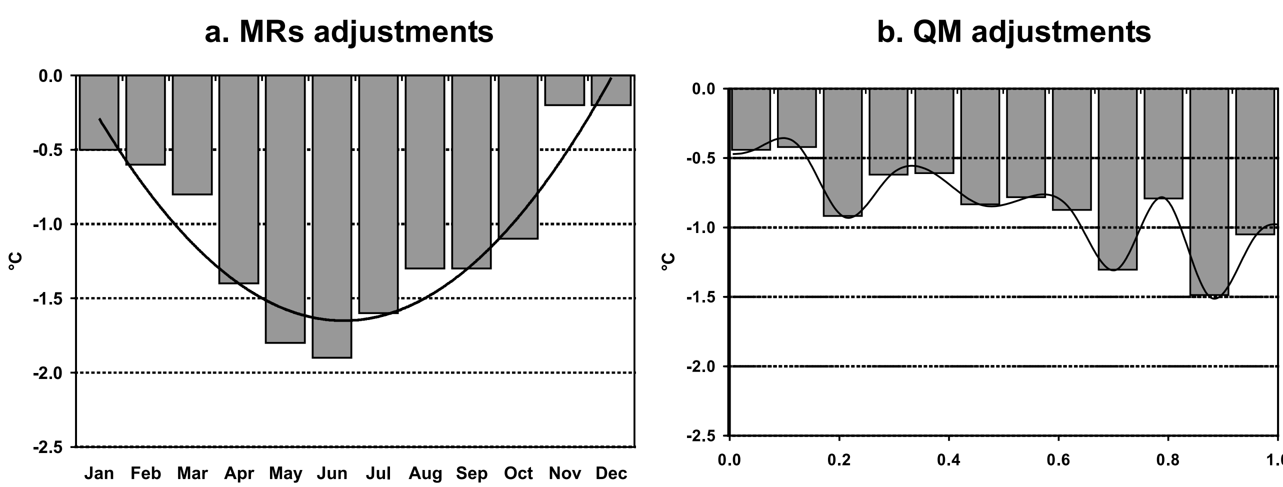

Figure 6. MRs and QM monthly adjustments for the changepoints 1965 at Brockville, Ontario. For the MRs adjustments, a polynomial of degree two (black) is fitted to the monthly shifts (gray) in order to produce 12 smoothed monthly adjustments (given at mid-point of each calendar month). For the QM adjustments, the difference between the 12 quantile categories, before and after 1965, is obtained (gray) for the cumulative frequency distribution along with the corresponding natural spline (black). The low frequencies correspond to cold winter months while high frequencies are associated to warm summer months.

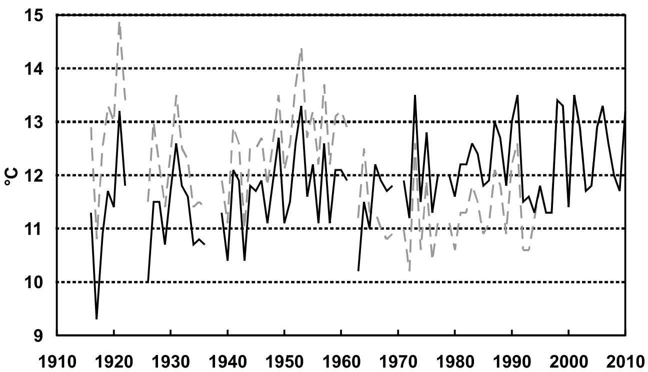

Figure 7. Annual mean of the daily maximum temperatures for Brockville, Ontario, before (gray – dashed line) and after (black – solid line) QM adjustment.

trends obtained at individual stations adjusted by the MRs and QM procedures are very similar over the same period of time: however, further testing is required to fully compare the MRs and QM adjustments. The annual mean series of Brockville daily maximum temperatures before and after QM adjustments are shown in Figure 7 (for which five changepoints were detected and adjusted for this series; see section 2.4).

[27] The QM procedure was applied to adjust monthly temperature series for the 173 and 185 shifts detected in maximum and minimum temperatures, respectively (Table 1). Whereas instrument relocations and other changes occurred at observing sites can cause either a rise or a drop in the observed temperature, the magnitude of all changes is not necessary symmetrical about zero. Figure 8 shows the frequency distribution of the monthly QM adjustments applied to the monthly mean series of the daily maximum or minimum temperatures. The vast majority of the adjustments vary from −3.0 to 3.0°C. The average of the monthly QM adjustments is −0.35°C for the maximum temperature data set and −0.29°C for the minimum temperature data set. This asymmetry is partly due to a decreasing shift often detected in the mid-1940s caused by the joining of station observations and relocations of the instruments at new airports. About 75% of the airport sites were located at a higher elevation than the original site, and the join of the station observations (or the instruments' relocation) have created a decreasing step in the unadjusted temperature time series due to colder temperature at the more elevated airport site. In general, instruments were often relocated to sites with better exposure, away from pavement and nearby buildings, creating a non-climatic decreasing step in their unadjusted temperature time series.

3. Trends Analysis

[28] Trends in annual and seasonal means of daily maximum, minimum and mean temperatures were examined at individual stations and for the country (the daily mean temperature is the average of the daily maximum and minimum). Since the climate observing network in the northern regions was established only during the late 1940s, there are very few locations in the north with temperature data prior to 1945. For this reason, the trends were examined for two periods: 1950–2010 for Canada (the entire country) and 1900–2010 for Southern Canada (south of 60°N). In addition, for the computation of average spatial trends, observations from the irregularly distributed climate stations had to be interpolated to evenly spaced grid point locations for equal representation across the country. Therefore, the monthly, seasonal, and annual temperature anomalies (departures from the 1961–1990 average) obtained at individual stations were interpolated to the 50 km spaced grid points (CANGRD, E. Milewska and R. D. Whitewood, Tool for monitoring areal climate trends in Canada, unpublished manuscript, 2011) using the statistical method of Gandin's Optimal Interpolation [*Gandin*, 1965; *Bretherton et al.*, 1976; *Alaka and Elvander*, 1972]. Seasonal and annual grid point values were then averaged to produce the annual and seasonal time series for Canada and Southern Canada. All linear trends were estimated using the approach by *Sen* [1968] and the statistical significance of the trend was assessed at the 5% confidence level using the Kendall's test [*Kendall*, 1955]. Trends at the stations were computed only if more than 80% of the values were present in the series.

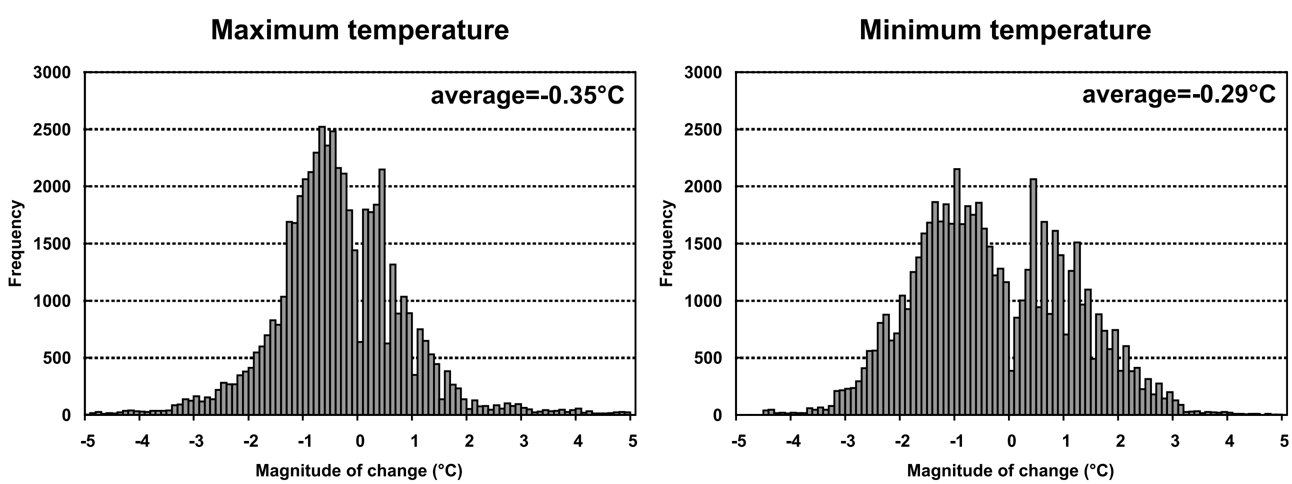

Figure 8. Frequency distribution of the QM adjustments applied to the monthly mean of the daily maximum or minimum temperatures (for the 173 and 185 shifts detected in the maximum and minimum temperature, respectively).

Table 2. Annual and Seasonal Temperature Trends for Canada 1950–2010 (°C/61 Years) and for Southern Canada 1900–2010 (°C/111 Years)

Period	Season	Maximum Temperature	Minimum Temperature	Mean Temperature
1950–2010	annual	1.4	1.7	1.5
	winter	2.1	2.7	2.3
	spring	1.6	1.9	1.7
	summer	1.0	1.2	1.1
	fall	1.3	1.6	1.4
1900–2010	annual	1.0	2.1	1.5
	winter	1.8	3.2	2.5
	spring	1.5	2.4	1.9
	summer	0.9	1.9	1.4
	fall	0.5	1.6	1.0

3.1. The 1950–2010 Trends in Canada

[29] The annual mean temperature in Canada has increased by about 1.5°C over 1950–2010 (Table 2). This warming is slightly more pronounced in the nighttime temperature (daily minimum) than the daytime temperature (daily maximum): the trends in maximum and minimum temperature are 1.4°C and 1.7°C, respectively, for the 61 years. The national series indicate that 2010 was the warmest year on record followed by 2006 and 1998, and the coldest year was 1972 (Figure 9). Positive trends are observed at almost all locations across the country: about 63% and 67% of the stations show significant increasing trends in their daytime and nighttime temperature, respectively (Figure 10). The nighttime warming is slightly greater than the daytime warming at most locations: the majority of the annual trends vary from 0.3 to 3.0°C in minimum temperature and from 0.3 to 2.5°C in maximum temperature.

[30] The seasonal mean temperature trends for Canada indicate that the greatest temperature change occurs during the winter with a positive trend of 2.3°C for 1950–2010 (Table 2). Spatially, the winter warming is mainly found in the western regions and in the south whereas several non-significant decreasing trends are identified in the east (Figure 10). At individual stations, most increasing trends range from 1.0 to more than 5.0°C over the 61 years for both winter daytime and nighttime temperature. During the spring, the magnitude of the warming is smaller but still considerable: the national series shows an increase of 1.7°C in mean temperature for 1950–2010. Even if increasing trends are observed at most locations across the country, there are still a few stations showing non-significant decrease in the eastern regions, particularly in nighttime temperature. Increasing spring temperature trends vary from 0.5 to 3.5°C over the past 61 years

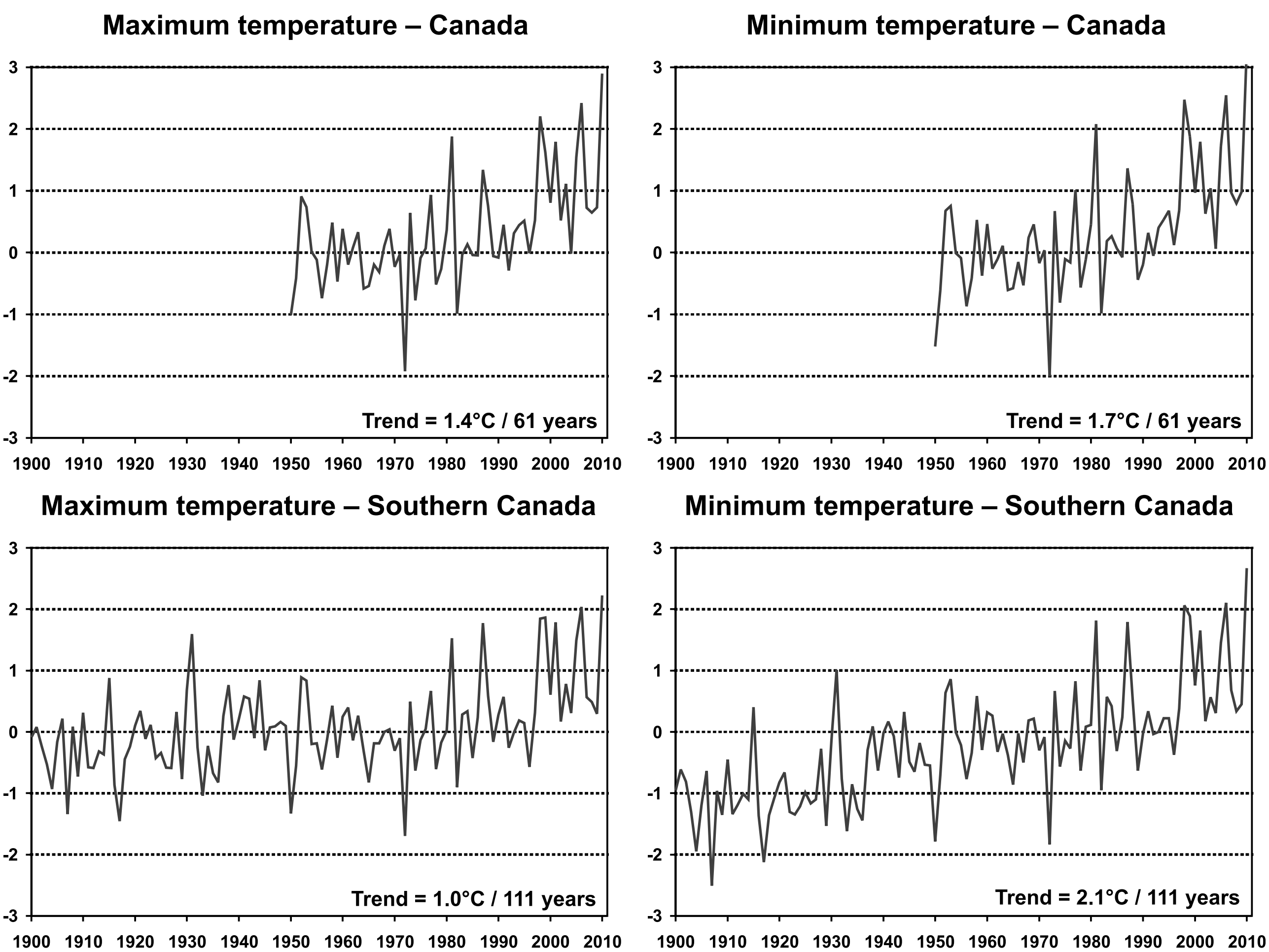

Figure 9. Annual mean maximum and minimum temperature anomalies for Canada, 1950–2010, and Southern Canada, 1900–2010.

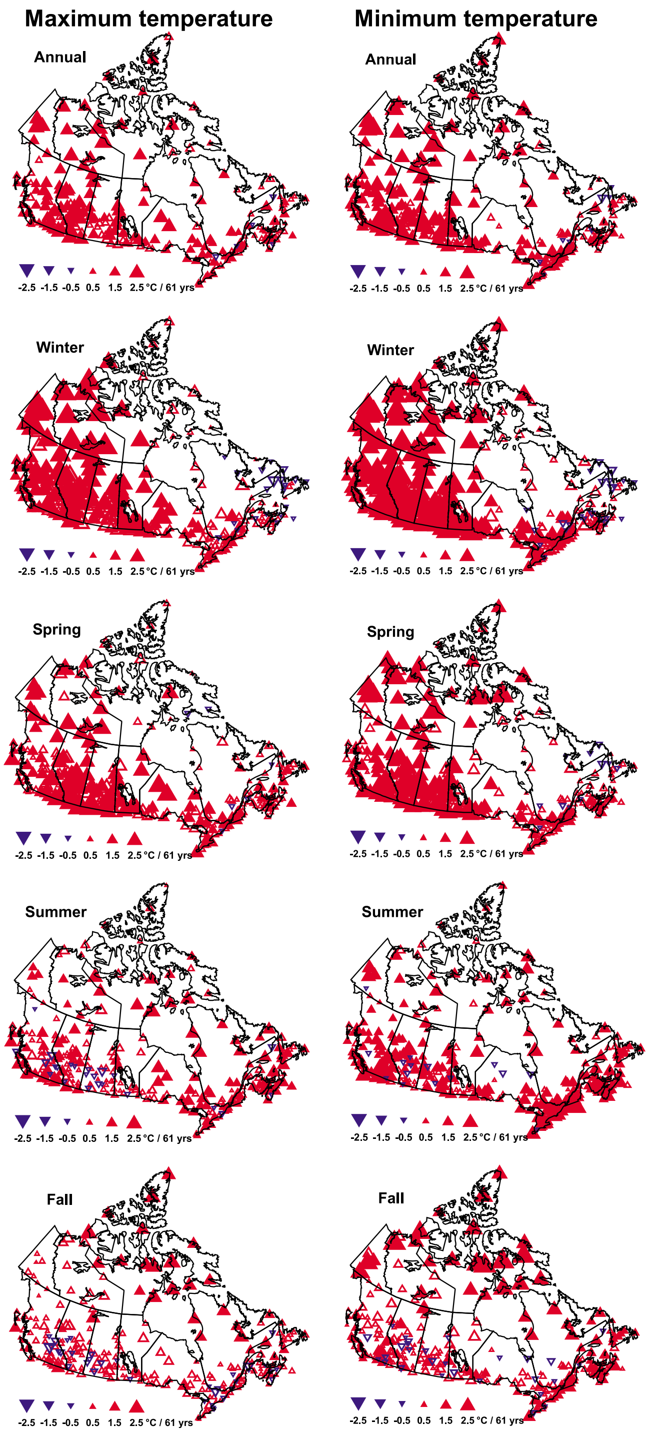

Figure 10. Trends in annual and seasonal mean of the daily maximum and minimum temperature for 1950–2010. Upward (red) and downward (blue) pointing triangles indicate positive and negative trends respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

at most locations and for both daytime and nighttime temperature.

[31] The warming in Canada is much weaker during the summer and fall. The national time series indicate an increase of 1.1°C in the summer mean temperature over 1950–2010 (Table 2). Spatially, the summer warming is observed across the country and most locations have trends ranging from 0.3 to 2.5°C for the past 61 years; however, there are still a number of locations showing non-significant decreasing trends in the Canadian Prairies, particularly for the daytime temperature (Figure 10). In the fall, there is a distinct pattern of mixed non-significant decreasing and increasing trends in the south (although that several significant increasing trends are also found in nighttime temperature) and significant increasing trends in the north and east. The significant trends during the fall vary from 1.0 to 3.5°C for the last 61 years in the northern and eastern regions. Overall, the national series indicates that the fall temperature has increased by 1.4°C over 1950–2010.

3.2. The 1900–2010 Trends in Southern Canada

[32] The annual mean temperature for Southern Canada has increased by 1.5°C for 1900–2010 (Table 2). The warming is considerably greater in the nighttime temperature compare to the daytime temperature: annual trends of 2.1°C and 1.0°C are observed over the past 111 years in the minimum and maximum temperatures, respectively. The annual nighttime temperature for Southern Canada shows a steady increase from the beginning to the end of the period whereas the daytime temperature indicates an increase from the 1900s to the beginning of the 1940s, followed by a slight decrease to the 1970s, and a considerable increase until 2010 (Figure 9). Although there are fewer stations in Southern Canada with enough data to compute the trends from 1900 to 2010 than for the shorter period, 63% and 92% of the long-term stations show a significant increase in their annual maximum and minimum temperature, respectively (Figure 11). At individual stations, the annual trends generally vary from 1.0°C to 3.5°C for nighttime temperature while they range from 0.5°C to 2.5°C for daytime temperature for 1900–2010.

[33] The seasonal trends for Southern Canada indicate that the greatest temperature change over the past 111 years also occur during the winter when the mean temperature increased by 2.5°C (Table 2). The temperature trend pattern is very

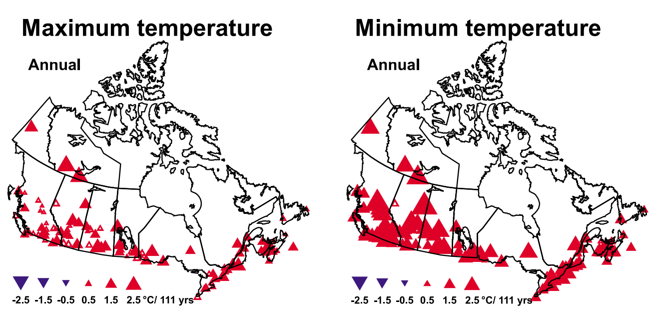

Figure 11. Trends in annual mean of the daily maximum and minimum temperature for 1900–2010. Upward (red) and downward (blue) pointing triangles indicate positive and negative trends respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

similar for winter and spring over the 1900–2010 period: almost all locations across the country have a significant positive trend. At most stations, the winter and spring trends vary from 2.0°C to more than 5.0°C for the minimum temperature and from 1.5°C to 4.5°C for maximum temperature. The warming in Southern Canada is much less during the summer and fall. During these two seasons, most stations show a significant increasing trend of 1.0 to 3.0°C in their nighttime temperature over the past 111 years whereas a mixed pattern of non-significant decreasing and increasing trends, and few significant increasing trends is observed in the daytime temperature across the country for 1900–2010.

4. Discussion

[34] In this study, the detection of changepoints was performed on the monthly temperature series of individual stations using two techniques, several neighbors and metadata. It took a considerable amount of time to assess the time series of 338 stations, maximum and minimum temperature separately, since the approach taken in this study requires making decisions in order to determine which of the detected shifts needs adjustment. The advantages were to be able to record the causes of inhomogeneities when available and to increase our understanding of their impact on temperature. Automated homogenization procedures have been recently developed to accelerate detection on monthly mean temperature time series [*Menne and Williams*, 2009; *Szentimrey*, 2008]. These procedures automatically identify changepoints through mutual comparison of series within the same climate region and they do not assume that the neighbor series are homogeneous. Although fully automated algorithms are highly desirable, local homogenized data prepared with some level of manual intervention are still needed to better understand the causes of inhomogeneities in temperature series and for use in validation of automated procedures.

[35] It was found in this study that about 65% of the time series were homogeneous. This seems to be a large number of homogeneous series as compared to results from other regions [*Venema et al.*, 2012]. Canada is a vast country with a relatively small number of stations covering long periods of time. A main challenge for homogeneity testing in Canada is that neighbor stations are usually far (within 200 km, and they can be as far as 700 km in the north). Since a shift was retained for adjustment only if it was identified with at least two neighbors, then many stations were declared homogeneous. About 60% of the stations were also found homogeneous in the first generation data sets [*Vincent and Gullett*, 1999].

[36] It is difficult to compare this new version of the data sets to the earlier version in terms of the frequency of adjustments since the input data are not the same. The number of stations is different (210 stations for the first generation and 338 stations for the second generation); the length of the time series is different (time series ending in early 2000s were tested for homogeneity in the first generation data sets while time series ending in 2010 were tested in the second generation data sets); in addition, the joining years and neighbors were sometimes different. Overall, for the same stations, same length of time series, same joining years and same neighbors, the frequency of the adjustments were the same.

[37] Trends calculated before and after adjustments were compared at individual stations. Since shifts were detected at various dates in time (Figure 5) and adjustments were either positive or negative (Figure 8), the impact of adjustments on the trends varies from station to station and for different periods of time (Figure 7). Overall, the adjustments that have affected the trends most were those for the change in observing time in 1961. In this case, the daily minimum temperature of many stations (120 stations) was adjusted for the decreasing step in 1961 (Figure 3). At these stations, the trends generally became more positive or reversing from negative to positive with the adjustments – in particular in the eastern regions of the country [*Vincent et al.*, 2009].

[38] There exist a very limited number of techniques for homogenizing daily climate data series. This is because daily data are much more variable spatially and seasonally; they are notably influenced by topography and local surroundings [*Trewin and Trevitt*, 1996]. Nonetheless, a few innovative techniques have been recently developed [*Della-Marta and Wanner*, 2006; *Toreti et al.*, 2010; *Wang et al.* 2010; *Mestre et al.*, 2011] and have been applied to daily temperatures [*Kuglitsch et al.*, 2009; *Brown et al.*, 2010; *Nemec et al.*, 2012]. Still, more work is needed to evaluate and compare methods for homogenizing daily temperatures and especially to determine the impact of automation [*Guttman and Baker*, 1996; *Milewska and Hogg*, 2002; *Sun et al.*, 2005]. The QM algorithm using a reference series is currently being tested for adjusting daily temperature in a region where the neighboring series can be relatively far and of a weaker correlation with the candidate series (such as found in Canada). After that, the QM algorithm will be used to adjust the daily temperatures of the Canadian stations for the shifts identified in the monthly series. This work on developing the second generation of homogenized daily temperatures will be reported in a separate study. For the time being, daily temperatures have been adjusted for the non-climatic shifts detected in the monthly temperature series in the current study using linear interpolation between the monthly adjustments (similarly to *Vincent et al.* [2002]); these homogenized daily temperatures are available from the lead author upon request.

5. Concluding Remarks

[39] Homogenized temperature time series data set was prepared for the analysis of trends at 338 locations across Canada. The various tasks involved can be summarized as follows:

[40] 1. Data of two, three or four co-located sites were combined together in order to produce longer time series. This was done at 63% of the stations (213 stations).

[41] 2. Daily minimum temperatures were adjusted for the change in observing time in July 1961 using a procedure based on hourly temperature observations. This affected daily minimum temperatures for the period 1961–2010 at about 36% of the stations (120 synoptic stations).

[42] 3. Monthly mean temperature anomalies were tested for temporal homogeneity using two statistical methods with neighboring stations. As a result, 66% of the maximum temperature series (224 stations) and 64% of the minimum temperature series (218 stations) were found to be homogeneous (no adjustments needed). A total of 190 stations did not

require any homogeneity adjustments for either the maximum or the minimum temperature series.

[43] 4. For temperature series with detected non-climatic shifts, the monthly mean series of daily maximum and/or minimum temperatures were adjusted to be in agreement with the most recent homogeneous part of the series in terms of temporal homogeneity. Such adjustments were applied to the maximum temperature series at 114 stations for a total of 173 shifts, and to the minimum temperature series at 120 stations for a total of 185 shifts.

[44] Several improvements were made in the second generation of homogenized temperature data sets as compared to the first generation. The station list was revised to include more locations with better spatial and temporal coverage. The temperature data of more co-located sites were joined together in order to produce a greater number of longer data time series. For the change in observing time in 1961, adjustments were applied to the affected daily minimum temperatures using an improved procedure based on hourly temperatures, whereas every day was adjusted in the first generation data sets using a procedure based on statistically estimated monthly adjustments. Homogeneity testing and adjustments were done thoroughly including the full period of record at each station in the second generation data sets whereas it was done on records with data up to the beginning of the 2000s in the first generation data sets. Two techniques were used to detect non-climatic shifts in de-seasonalized monthly mean of daily maximum and minimum temperature series separately in order to confirm the position in time of the non-climatic shifts. A new procedure based on a Quantile-Matching algorithm was used to obtain better estimates of the monthly adjustments.

[45] Annual and seasonal temperature trends were examined using the resulting homogenized data sets. The results show that the temperature has increased in Canada over the past 61 years (1950–2010) and that the warming is slightly more pronounced in the minimum temperature than in the maximum temperature over this period of time. The results are similar for Southern Canada although the warming is considerably greater in the minimum temperature compared to the maximum temperature over the past 111 years (1900–2010). Warming temperature is generally observed in all seasons and the greatest warming is found in winter and spring for both periods. Overall, similar results were found in *Zhang et al.* [2000]. In their study, the results showed an increase in temperature slightly greater in the minimum than in the maximum temperature for Canada over the period 1950–1998, and much more pronounced in the minimum temperature as compared to the maximum temperature for Southern Canada for 1900–1998. Their findings also showed that seasonally, the greatest warming was observed during winter and spring compared to summer and fall for both periods, which is in agreement with the findings of the current study.

[46] In conclusion, as of today, the second generation of homogenized monthly surface air temperature provides the best data sets for temperature trends in Canada along with detailed documentation on how the data sets were prepared. It is important to encourage homogenization work carried out by scientists who are likely to have access to local data and metadata and who are familiar with their own local geography and climate variations. Homogenized data sets prepared at regional and national level can be helpful to complete and validate large/global homogenized data sets prepared by the scientific community. The Second Generation of Homogenized Canadian Monthly Surface Air Temperature is now available as part of the Adjusted and Homogenized Canadian Climate Data (AHCCD) at http://www.ec.gc.ca/dccha-ahccd/.

[47] **Acknowledgments.** The authors would like to thank Francis Zwiers from the Pacific Climate Impacts Consortium, University of Victoria, Canada, and Xuebin Zhang and Eva Mekis from the Climate Research Division, Sciences and Technologies Branch of Environment Canada, as well as three anonymous reviewers for their helpful comments and suggestions that have helped improve the manuscript.

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