Characteristics of Daily and Extreme Temperatures over Canada

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ABSTRACT

Recent studies have shown that, since 1900, mean annual temperature over southern Canada has increased by an average of 0.9°C, with the largest warming during winter and early spring. Every season was associated with greater increases in minimum temperature as opposed to maximum, thus resulting in a significant decrease in the daily temperature range (DTR). The second half of the twentieth century was associated with significant winter and spring warming in the south and west, and cooling in the northeast. However, no significant changes in DTR were observed during this period. This investigation goes beyond the annual/seasonal scales by examining trends and variability in daily minimum and maximum temperature with particular emphasis on extremes. Using recently updated, homogenized daily data, spatial and temporal characteristics of daily and extreme temperature-related variables are analyzed on a seasonal basis for the periods of 1900–98 (southern Canada), and 1950–98 (the entire country). From 1900 to 1998, the majority of southern Canada shows significantly increasing trends to the lower and higher percentiles of the daily minimum and maximum temperature distribution. The findings translate into fewer days with extreme low temperature during winter, spring, and summer and more days with extreme high temperature during winter and spring. No consistent trends are found for the higher percentiles of summer daily maximum temperature, indicating little change to the number of extreme hot summer days. Over the southwest, increases are larger to the left-hand side of the daily minimum and maximum temperature distribution, resulting in significant decreases to the intraseasonal standard deviation of daily temperature. The 1950–98 results are somewhat different from the entire century, especially, during winter and spring. This result includes significant increases to the low and high percentiles over the west, and decreases over the east. This analysis reveals that the largest individual daily temperature trends (both minimum and maximum) occur during winter and early spring, when substantial warming is observed. For summer, increases are only associated with daily minimum temperature. Autumn displays varying results, with some late season cooling, mainly over western regions. The observed warming trends have a substantial effect on several economically sensitive indices. This effect includes significant increases in the number of growing and cooling degree days and significant decreases in heating degree days. In addition, the length of the frost-free period is significantly longer over most of the country.

1. Introduction

The detection and attribution of global climate change resulting from anthropogenic activities are one of the main themes of current climatological research. Recent investigations have shown an increase in global mean temperature of approximately 0.4°–0.8°C during the twentieth century (e.g., Panel on Reconciling Temperature Observations 2000); however, this trend has not been uniform either spatially or temporally. Many previous studies [including those incorporating general circulation models (GCMs)] focused on changes in long-term average (i.e., annual, seasonal) temperature (e.g., Kattenberg et al. 1996). Another important aspect involves characteristics of daily temperature and in particular, changes to the extreme ends (or tails) of the daily temperature distribution. Numerous task groups, including the Intergovernmental Panel on Climate Change (IPCC), have identified the detection of trends and variability in extreme temperatures as critical factors toward an improved understanding of past and potential future global change. To describe accurately the spatial and temporal characteristics of daily and extreme temperatures, long-period time series of reliable and homogeneous daily values are required. For Canada, such high quality datasets have been created recently for daily minimum, maximum, and mean temperature (Vincent et al. 2000). This study uses these data to examine twentieth-century trends and variability in daily temperature characteristics (with particular emphasis on the extreme ends of the daily temperature distribution) over Canada.

Recently, there have been several observational analyses involving daily and/or extreme temperature trends and variability over various regions of the globe. The majority of the findings revealed significant decreases

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in days with extreme low daily temperature but no significant increases in the number of extreme warm days [e.g., over the contiguous United States (Karl et al. 1996); Great Britain (Jones et al. 1999); northern and central Europe (Brazdil et al. 1999); Australia and New Zealand (Plummer et al. 1999); and China (Zhai et al. 1999)]. Most of these regions also experienced a decrease in various measures of intraseasonal daily temperature variability due to the fewer days with extreme low minimum temperature and no corresponding increases in days with extreme high maximum temperature (e.g., Karl et al. 1995; Collins et al. 2000). A more detailed review of twentieth-century trends in various extreme climate events over the world (including temperature) is found in Easterling et al. (2000).

Specifically for Canada, Zhang et al. (2000a) examined annual and seasonal temperature and precipitation trends during the twentieth century. Results showed that, from 1900 to 1998, annual mean temperature over southern regions of the country has increased by an average of 0.9°C, with the largest increases during winter and spring. Summer generally displayed less warming, and autumn was associated with small cooling trends. During every season, increases were greater for daily minimum temperature as opposed to maximum, thus resulting in significant decreases in the daily temperature range (DTR) over most of southern Canada. The 1950–98 period was associated with distinct regional differences, including significant warming in the south and west and cooling in the northeast (particularly, during winter and spring). Minimum and maximum temperature trends were similar in magnitude, and, as a result, no significant changes in DTR were observed during the second half of the century. The decreases in minimum temperature over the east, and the small changes in DTR over most of Canada are both unusual in terms of observed trends over most other land regions of the world in recent decades (Easterling et al. 1997).

Kharin and Zwiers (2000) analyzed global extreme temperatures using an ensemble of transient climate change simulations from the Canadian Centre for Climate Modelling and Analysis first-generation Global Coupled Model. The evolution of greenhouse gases and aerosols in the simulations was consistent with the IPCC 1992 scenario A (Leggett et al. 1992). The projected change (in comparison with the 1975–95 reference period) in globally averaged 20-yr return values of daily minimum temperature between 2040 and 2060 was 2.4°C and between 2080 and 2100 was 5.2°C. Increases to the 20-yr return values of daily maximum temperature were 1.8°C and 3.9°C, respectively. The changes were substantially larger for extreme daily minimum temperature over land areas in both hemispheres and over high-latitude oceans, where snow and sea ice retreated. Greatest increases to extreme daily maximum temperature occurred over central and southeastern North America, central and southeastern Asia, and tropical Africa, mainly due to large decreases in soil moisture.

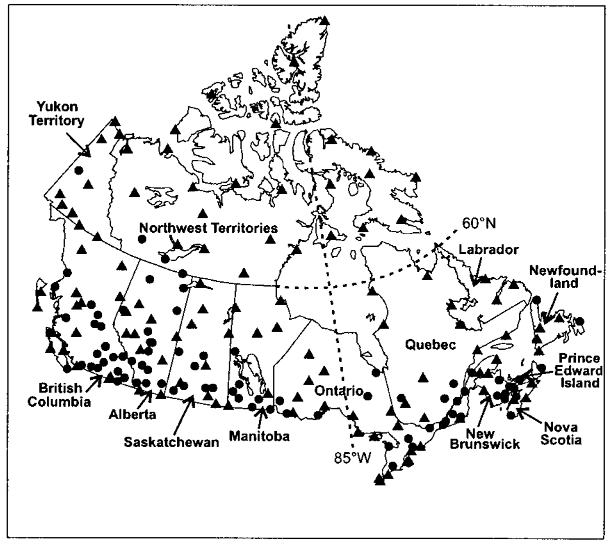

FIG. 1. Locations of the 210 temperature stations in this investigation. Filled circles represent the 86 long-term stations used in the trend analyses from 1900 to 1998, and filled triangles denote the remaining stations. All stations are used for the 1950–98 trend analyses.

To obtain a better overall understanding of both past and potential future changes to global temperature, analyses at the daily timescale are required. Therefore, the main objective of this study is to go beyond the annual/seasonal scales and to examine characteristics of daily temperature over Canada. Particular emphasis is placed on analyzing trends and variability in the extreme ends of the daily minimum and maximum temperature distribution. Using the best available daily temperature data, spatial and temporal aspects of the daily and extreme variables are investigated on a seasonal basis for the periods 1900–98 and 1950–98. The study concludes with an examination of trends in several economically sensitive, daily temperature–related indices. The data and methodology are discussed in section 2, and results regarding the analyses of extreme temperature, daily temperature, and economic indices are presented in section 3. A summary and discussion of the findings follow in section 4.

2. Data and methodology

Temperature data consist of daily minimum, maximum, and mean values for 210 high quality (i.e., few missing values, minimal urban effects), relatively evenly distributed stations across Canada (Fig. 1). For these data, homogeneity problems caused by station relocation and changes to instrumentation and observing practices have been addressed using a regression model technique (Vincent 1998). Monthly adjustment factors were obtained for identified inhomogeneities and a database of homogenized monthly minimum, maximum, and mean values was created (Vincent and Gullett 1999).

These monthly factors were then further interpolated into daily factors that were used to obtain the adjusted daily temperatures (Vincent et al. 2000). This has resulted in a new, preliminary daily temperature database used in this investigation. Because of the lack of climatological observations prior to the 1950s over northern regions of the country, this analysis focuses on two periods. The first (1900–98) involves stations over more southern regions of Canada where data have generally been gathered since near the beginning of the twentieth century (see Fig. 1). The second period (1950–98) utilizes all 210 stations. For all variable and trend calculations, individual stations must report at least 80% of their values (for the period in question) otherwise, the station is not used in the analysis.

Trends in temperature percentiles are used to assess changes in the distribution of daily temperature over Canada (including extremes). For each station, the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of both the daily minimum and daily maximum temperature distributions are estimated (°C) on a seasonal basis for every year. Seasons are defined as winter [December–January–February (DJF)], spring (MAM), summer (JJA), and autumn (SON). There are numerous empirical plotting position formulas that can be used to obtain smooth estimates of the aforementioned percentiles. This investigation incorporates the formula introduced by Beard (1943) and described in detail by Jenkinson (1977). Daily temperatures for each season are first ranked in ascending order $X_1, X_2, \ldots, X_N$. The probability P that a random value is less than or equal to the rank of that value X_m is estimated by

$$P = (m - 0.31)/(N + 0.38).$$

For example, if a season contains 90 values, the temperature representing the 99th percentile is linearly interpolated between the 90th-ranked value (corresponding to $P = 99.2\%$) and the 89th-ranked value ($P = 98.1\%$). Reasons for choosing an empirical plotting position formula to estimate the percentiles (as opposed to fitting a statistical distribution such as gamma) include simplicity, as well as, avoiding any assumptions of the underlying distribution. Comparisons between various percentiles using the aforementioned formula versus those from a two-parameter gamma distribution generally reveal small differences in the estimated values. More important, the long-term trend and variability in the two estimates are virtually identical. The advantage of percentiles is that they are comparable among the greatly varying climates of Canada (as well as with other areas of the globe). Other extreme and economically sensitive, daily temperature–related indices are defined as they are presented.

This study focuses on observed trends in daily and extreme temperatures during the twentieth century. The trend calculation is the same as that incorporated by Zhang et al. (2000a) who examined seasonal temperature and precipitation trends over Canada. It involves a statistical model that takes into account serial correlation; a problem often encountered in the identification of linear trends in a climate series. In this model, the lag one autocorrelation of the time series is removed. Both the magnitude and statistical significance of the trend are then obtained based on the nonparametric Kendall's tau (Sen 1968). The advantage of the Kendall's tau is that it is less sensitive to the nonnormality of the distribution and is less affected by outliers (as compared with the least squares method). A detailed description of this technique is found in Zhang et al. (2000a). All trends in this investigation are assessed at the 5% significance level.

3. Results

a. Extreme temperature

This section examines characteristics of extreme temperature–related variables over Canada. Extreme low (high) temperatures are defined by the 1st, 5th, and 10th (90th, 95th, and 99th) percentiles of the daily minimum and maximum temperature distribution. Figures 2a–d and 3a–d present seasonal trends in the magnitude of the 5th and 95th percentiles (°C) for the periods of 1900–98 and 1950–98, respectively. Note that trends in the 1st, 10, 90th, and 99th percentiles (not shown) are similar to those in Figs. 2 and 3. In addition, trends in threshold exceedence frequency (i.e., the number of days with temperatures less than the lower and greater than the higher percentiles relative to the 1961–90 mean climate) are also analyzed (not shown) with results indicating similar changes to extreme temperatures as those in Figs. 2 and 3.

Figure 2a shows that from 1900 to 1998, winter daily minimum temperature over most of southern Canada had significant increases to the percentiles used to define extreme low and extreme high values. In terms of magnitude, the 5th percentiles have increased more than the 95th. This was also associated with a significant decrease in the number of days with extreme low minimum temperatures during this period, and a significant increase in days with extreme high minimum values (not shown). The majority of stations had significant increases to the 95th percentiles of daily maximum temperature (accompanied by increases in the number of days with extreme high winter maximum temperature). The 5th percentiles also show increases; however, they are generally not significant and confined to western regions. The spatial patterns for spring (Fig. 2b) are similar to winter for both daily minimum and maximum temperature with slight differences in the strength and significance of the trends. Summer minimum temperature also shows significant increases to both low and high percentiles over southern Canada. Trends in the daily maximum temperature percentiles, however, display little change with only a few significant increases to the low percentiles over the southern prairies. The varied 95th

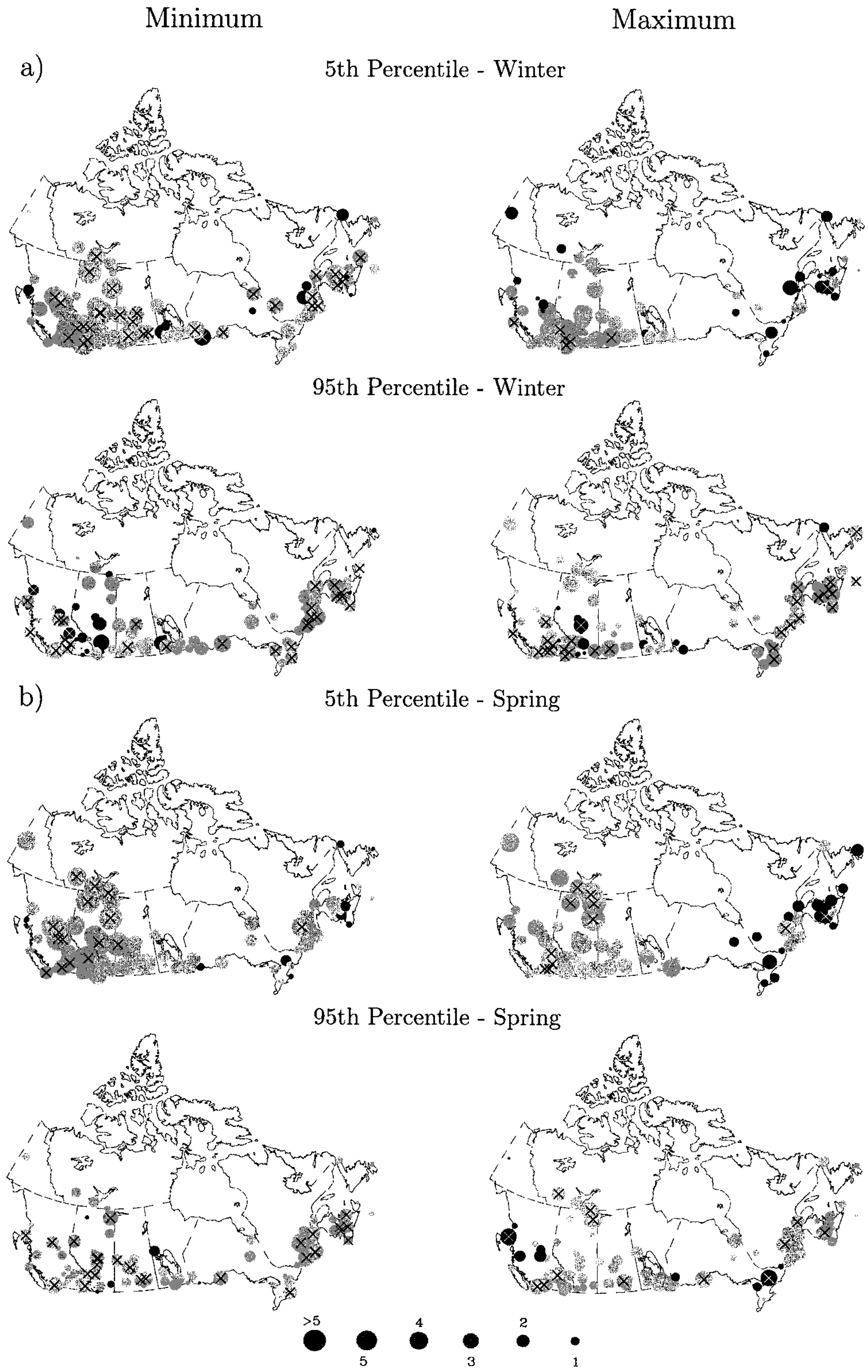

FIG. 2. Trends in the 5th and 95th percentiles of daily minimum and maximum temperature from 1900 to 1998 for (a) winter, (b) spring, (c) summer, and (d) autumn [°C (99 yr)$^{-1}$]. Dots are scaled according

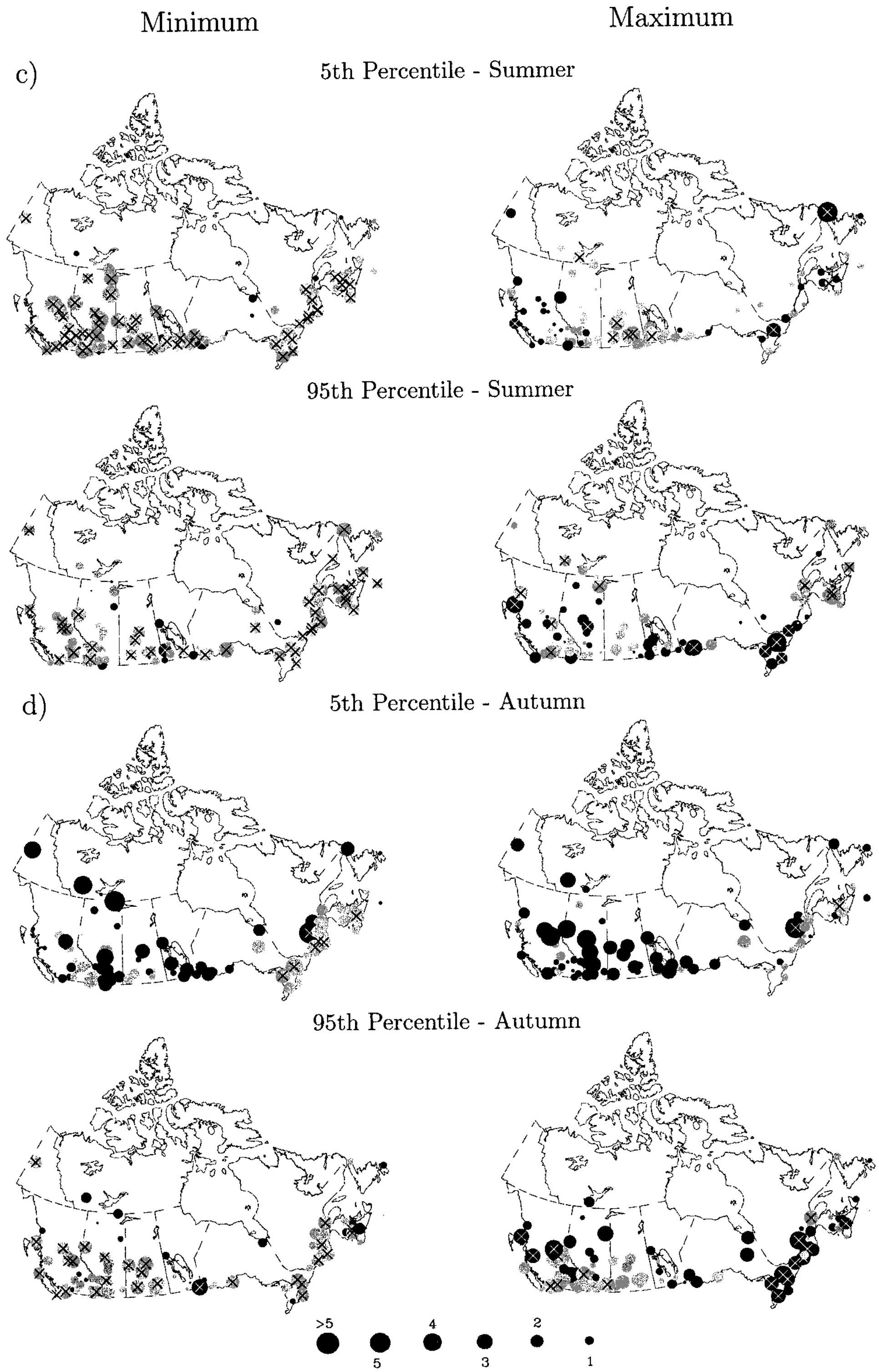

FIG. 2. (*Continued*) to the amplitude of the trend, with light gray signifying positive trends and black, signifying negative trends. Crosses denote trends significant at the 5% level.

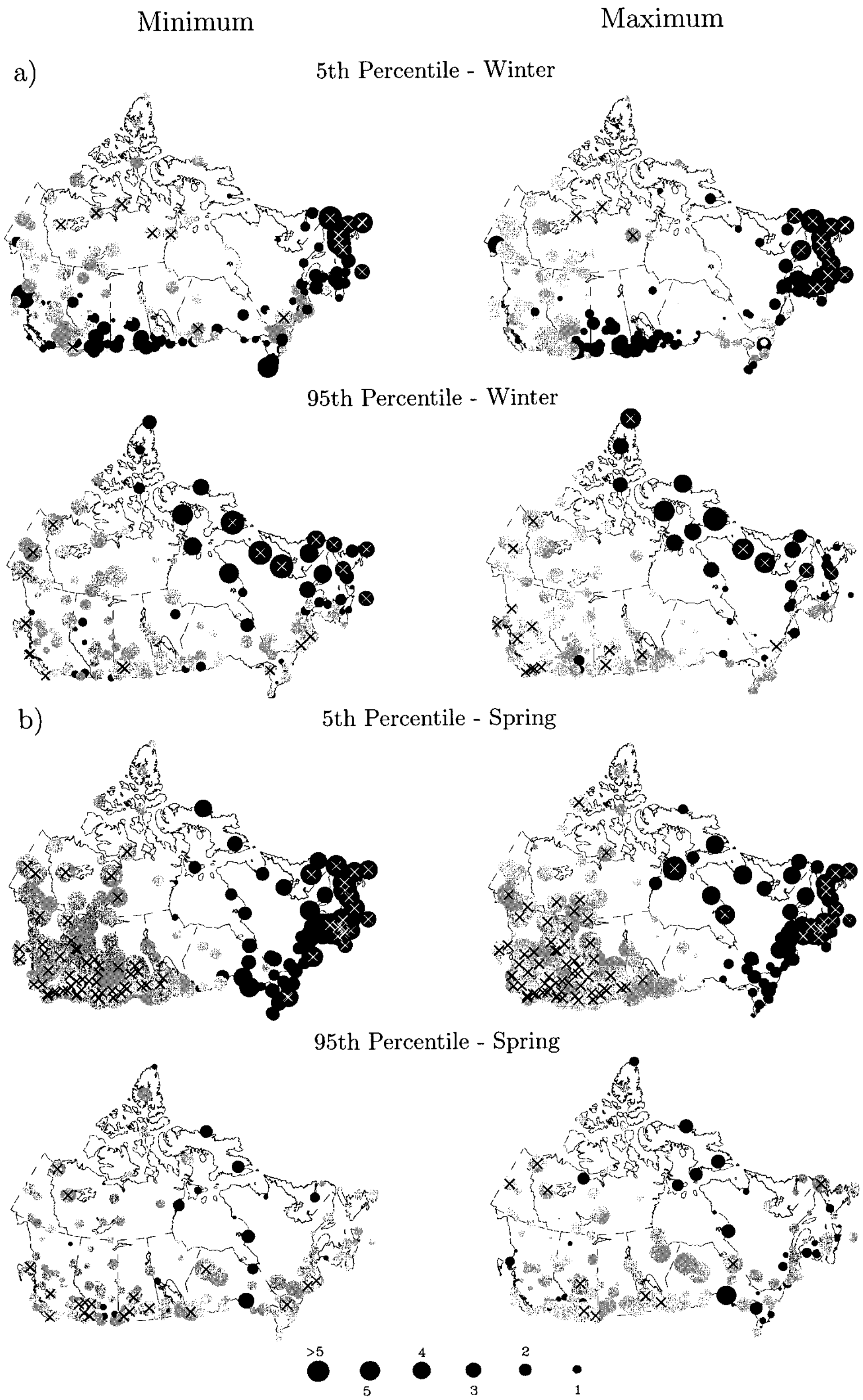

FIG. 3. Same as Fig. 2 but from 1950 to 1998 [°C (49 yr)$^{-1}$].

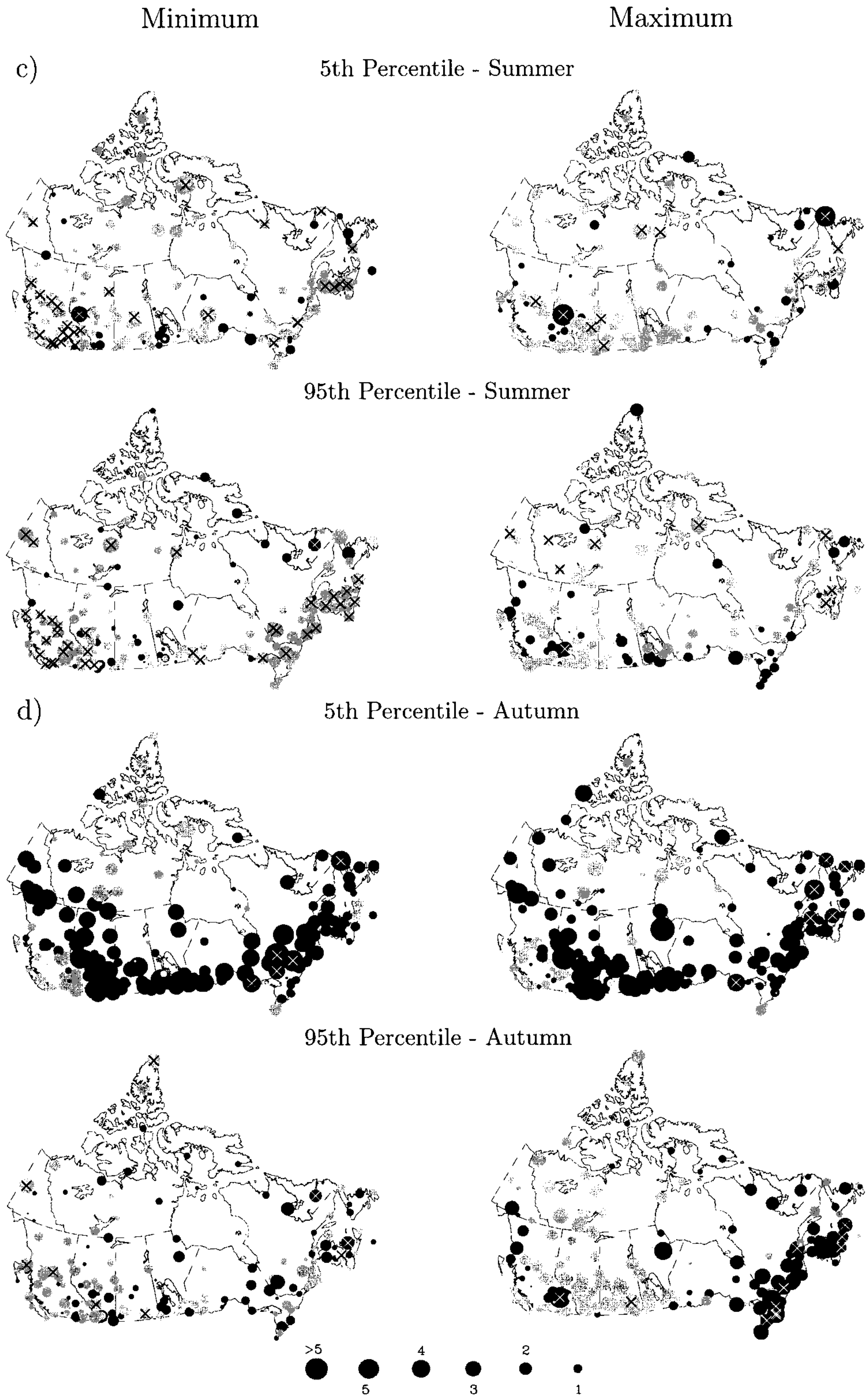

FIG. 3. (*Continued*)

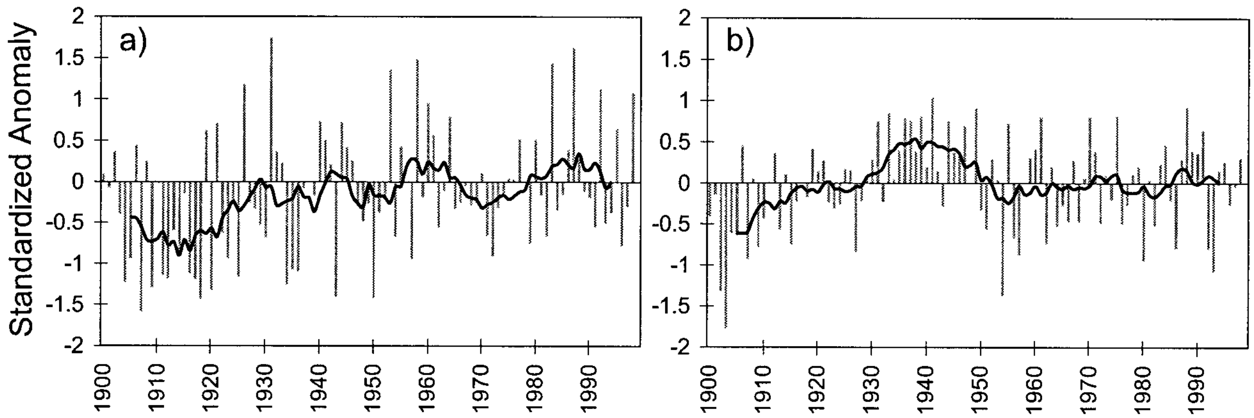

FIG. 4. Average standardized anomalies over southern Canada from 1900 to 1998 for (a) the 5th percentile of daily minimum temperature during winter and (b) the 95th percentile of daily maximum temperature during summer. Solid lines represent the 10-yr running means.

percentile pattern indicates no consistent changes to the temperature magnitude representing extreme hot summer days over Canada. Autumn is somewhat different from the other seasons. Daily maximum temperature generally shows statistically nonsignificant decreases to the 5th percentiles, while the higher percentiles have a varied pattern with increases in the southwest and decreases in the east (significant over southern Ontario and Quebec). Daily minimum temperature trends are associated with little spatial consistency in the low percentiles, but the 95th percentiles have significantly increased over most of southern Canada.

Seasonal trends from 1950 to 1998 (Figs. 3a–d) display more regional differences, especially during winter and spring. This includes increases to the lower and higher percentiles of daily minimum and maximum temperature over the west, and decreases over the east. The strongest and most significant responses are associated with the spring 5th percentiles where increases (decreases) near 5°C over the 49-yr period are observed over western (eastern) Canada. Conversely, spring trends in the 95th percentiles show smaller increases over most of the country. Summer (Fig. 3c) does not display a west–east split in the trends. As with 1900–98, the low and high percentiles of daily minimum temperature have significantly increased. There appears to be no consistent significant trend in the higher percentiles of maximum temperature in summer, except over northern regions where a few stations have significant increases. Autumn again tends to differ from the other seasons with most of the country showing decreases to the 5th percentiles of daily minimum and maximum temperature, and varied patterns in the 95th percentiles.

In summary, Figs. 2 and 3 reveal several significant trends (mostly increasing) in the various percentiles used to define extreme daily minimum and maximum temperature. Even though spatial and temporal differences exist, the results essentially translate into significant trends toward fewer days with extreme low temperature during winter, spring, and summer and more days with extreme high temperature during winter and spring. There appears to be no consistent trends regarding extreme high daily maximum summer temperature. Autumn is more variable, with several percentiles associated with cooling trends.

The linear trends in Figs. 2 and 3 provide limited information regarding interannual and interdecadal variability in the various percentiles. Insight into this variability is provided in Fig. 4, which shows the 1900–98 time series of average standardized anomalies over southern Canada for the 5th percentile of daily minimum temperature during winter (representative of extreme low winter temperatures) and the 95th percentile of daily maximum temperature during summer (i.e., extreme high summer daytime temperatures). Southern Canada refers to all the long-term stations south of 60°N. For every year, the standardized anomalies (with respect to the 1961–90 mean climate) are determined for each station on a seasonal basis and then averaged for all stations. Regarding the 5th percentile of winter minimum temperature, Fig. 4a shows a fairly consistent increase throughout the century (although there is evidence of interannual and interdecadal variability). This is consistent with Fig. 2a, which shows significant increases to this value over most of southern Canada. Conversely, the 95th percentile of summer maximum temperature (Fig. 4b) displays considerably more decadal-scale variability (particularly, during the first half of the century) with little evidence of a long-term trend. The 1930s and 1940s were the period during which the magnitude of this percentile was maintained at its highest. A closer inspection reveals that, during the 1930s these values were highest over western regions of the country, and during the 1940s they were highest over eastern regions. This explains the lack of consistent trends to the 95th percentiles of daily maximum summer temperature in Fig. 2c.

Further indication of the trends and temporal variability in extreme low and high daily temperatures is given in Fig. 5. For each of the 82 long-term stations

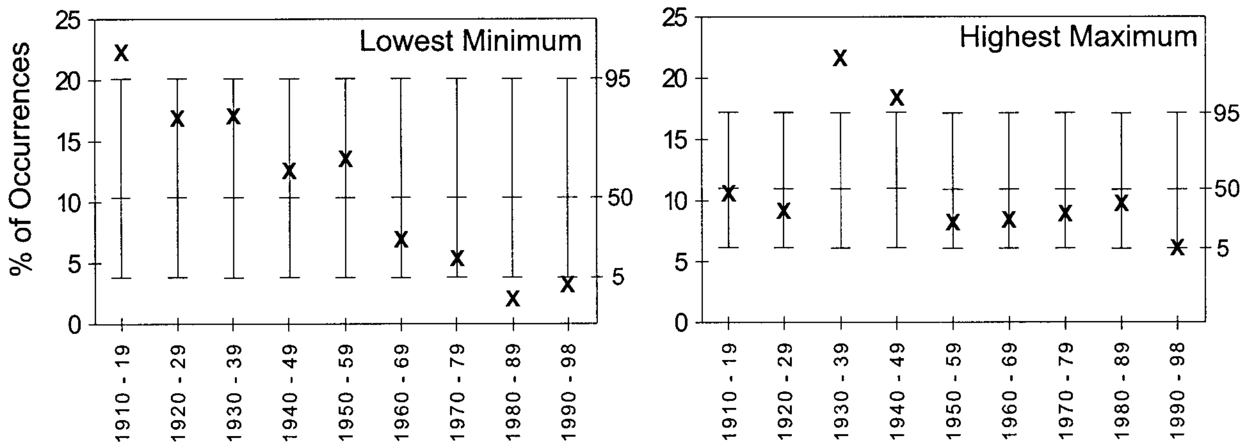

FIG. 5. Percentage occurrence (by decade) of the five lowest annual minimum and the five highest annual maximum daily temperatures recorded at 82 stations over southern Canada (south of 60°N) for the period of 1910–98. Observed percentages are denoted by an ×. Error bounds displaying the 5th, 50th, and 95th percentiles for each decade (as determined by a permutation procedure involving 1000 random simulations) are also provided (see text for details).

over southern Canada, the five lowest annual minimum and five highest annual maximum daily temperatures (from 1910 to 1998) are identified and their percentage occurrence by decade is calculated (denoted by the "×"s in Fig. 5). For minimum values, annual extremes are determined using the July–June definition of a year (i.e., from July 1909 to June 1998); for maximum temperatures, the standard January–December year is utilized. An indication of the natural variability in these observed values is also provided by incorporating a permutation procedure involving 1000 random simulations. For the 89 years in question, both the annual minimum and maximum extremes from each of the 82 stations are randomly shuffled (in the same manner, thereby maintaining spatial relationships) and the percentage occurrence analogous to the observed values in Fig. 5 is determined. This procedure is repeated 1000 times and the 5th, 50th, and 95th percentiles of the random frequency distributions are determined on a decadal basis. These percentiles are then averaged (for the nine decades) to produce error bounds representing values that would be expected in a trendless time series. Figure 5 reveals a consistent decrease in the frequency of extreme low daily temperatures during the past century (especially, following the 1960s). In addition, the number of extremes between 1910 and 1919 exceeded the 95th percentile of natural variability, and those from 1980 to 1989 and 1990 to 1998 were lower than the 5th percentile. This agrees with the previous findings of significant trends toward fewer days with extreme low minimum winter temperature over southern Canada. The 1930s and 1940s were, by far, the period during which most extreme high daily temperatures were recorded. During both decades, the percentage of occurrence was significantly higher than the calculated bounds of natural variability.

Changes in the 20-yr return values of annual minimum and annual maximum daily temperature are also examined. For each southern Canadian station, the 20-yr return values are estimated by fitting the generalized extreme value (GEV) distribution to the annual extremes of daily minimum and maximum temperature during the periods of 1900–49 and 1950–98. Differences in return values between the two periods are then calculated and tested for significance using a Monte Carlo procedure involving 1000 random simulations. The GEV distribution has been used by other investigations (e.g., Kharin and Zwiers 2000) to examine global (including Canadian) changes to daily temperature extremes. A description of this technique (calculation, advantages, limitations) is found in Kharin and Zwiers (2000).

With regard to daily minimum temperature, Fig. 6a shows increases over all southern Canada with highest values over central Alberta and Saskatchewan (4°C) and New Brunswick and Nova Scotia (3°C). Differences are significant for a few stations in these areas and correspond to an increase from near −48°C during 1900–49 to near −44°C during 1950–98 over west-central Saskatchewan; and −33° to −30°C in central New Brunswick. Figure 6b reveals that, with the exception of northeastern Quebec and Newfoundland, there has been a decrease in the 20-yr return values of daily maximum temperature over southern Canada. Differences are near −1°C over most regions with a small area of southern Ontario below −2°C. Only a few stations are statistically significant. This translates to a decrease in values from approximately 40°C in 1900–49 to about 38.5°C during 1950–98 over southern Saskatchewan. They are reduced from 38° to 36°C over southern Ontario. The decreases are likely the result of the large number of extreme high daily maximum temperatures during the 1930s and 1940s as revealed in Figs. 4b and 5.

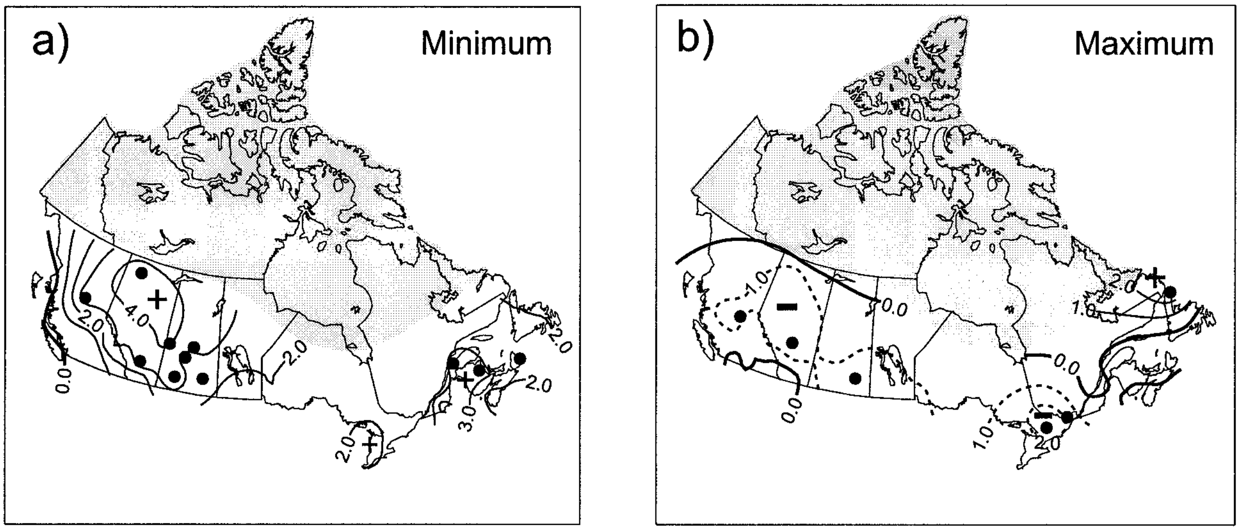

FIG. 6. Differences in 20-yr return values between the periods of 1900–49 and 1950–98 (1950–98 minus 1900–49) for (a) the annual extremes of daily minimum temperature and (b) the annual extremes of daily maximum temperature. Contour interval is 1.0°C. Negative values are dashed, and the 0.0 contour is thickened. Stations significantly different at the 5% level are denoted by filled circles. Regions with insufficient data are shaded.

b. Daily temperature

Results from section 3a indicate some significant changes to the extreme ends of the daily minimum and maximum temperature distributions. Changes to the entire probability distribution are analyzed by plotting seasonal trends in the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of daily minimum and maximum values. Because of previously outlined regional differences between western and eastern Canada, average trends from 1900 to 1998 are separated into southwestern and southeastern areas (Fig. 7). These are defined as long-term stations south of 60°N and separated by 85°W (see Fig. 1). This boundary is subjectively chosen based on several of the trend maps in Fig. 2 (and from other variables not shown). Southwestern Canada refers to the four western provinces plus northwestern Ontario, and southeastern Canada refers to the rest of the country south of 60°N. Average trends for all southern Canada are also examined (not shown), but because of regional differences during most seasons the results often cancel each other.

The plots in Fig. 7 reveal considerable information regarding regional trends and changes to the distribution of daily temperature. Over the southwest, lower percentiles of minimum and maximum temperature have increased at a greater rate than the higher percentiles during winter, spring, and summer (with differences more pronounced for minimum values). The larger increases to the left-hand side of the daily temperature distributions (compared to the right-hand side) indicate changes to the shape of these distributions (i.e., they are becoming more positively skewed). This is associated with significant decreases in the intraseasonal standard deviation of daily minimum and maximum temperature over western Canada during these seasons (not shown). Autumn is opposite with cooling in the lower percentiles and warming in the higher. This is associated with an increase in the standard deviation of autumn daily temperature during the twentieth century. Decreases to the lower percentiles of daily minimum and maximum autumn temperature suggest that the majority of the observed cooling has occurred later in this season.

Unlike the west, lower percentiles have not increased at a greater rate than the higher percentiles over southeastern Canada (except for autumn maximum). In fact, daily minimum temperature during all seasons shows a relatively uniform increase over the entire distribution, thereby indicating little change to the shape of these distributions. Only the mid- to higher percentiles of winter and spring daily maximum temperature have increased. For these seasons, this translates into an increase in daily maximum temperature standard deviation. Summer maximum temperature shows very little change to the entire distribution. The higher percentiles reveal some spatial differences over eastern Canada, with southern Ontario and Quebec displaying a significant decrease and extreme eastern Canada displaying a significant increase (see the 95th percentile of maximum temperature in Fig. 2c). Autumn maximum values are again different from other seasons, with increases to the lower and decreases to the higher percentiles. Note that, for every season over both southwestern and southeastern Canada, minimum daily temperature has increased more than maximum, which is consistent with the observed significant decreases in DTR during the twentieth century (Zhang et al. 2000a).

Similar analyses are carried out for the second half of the century. Regions examined include southwestern,

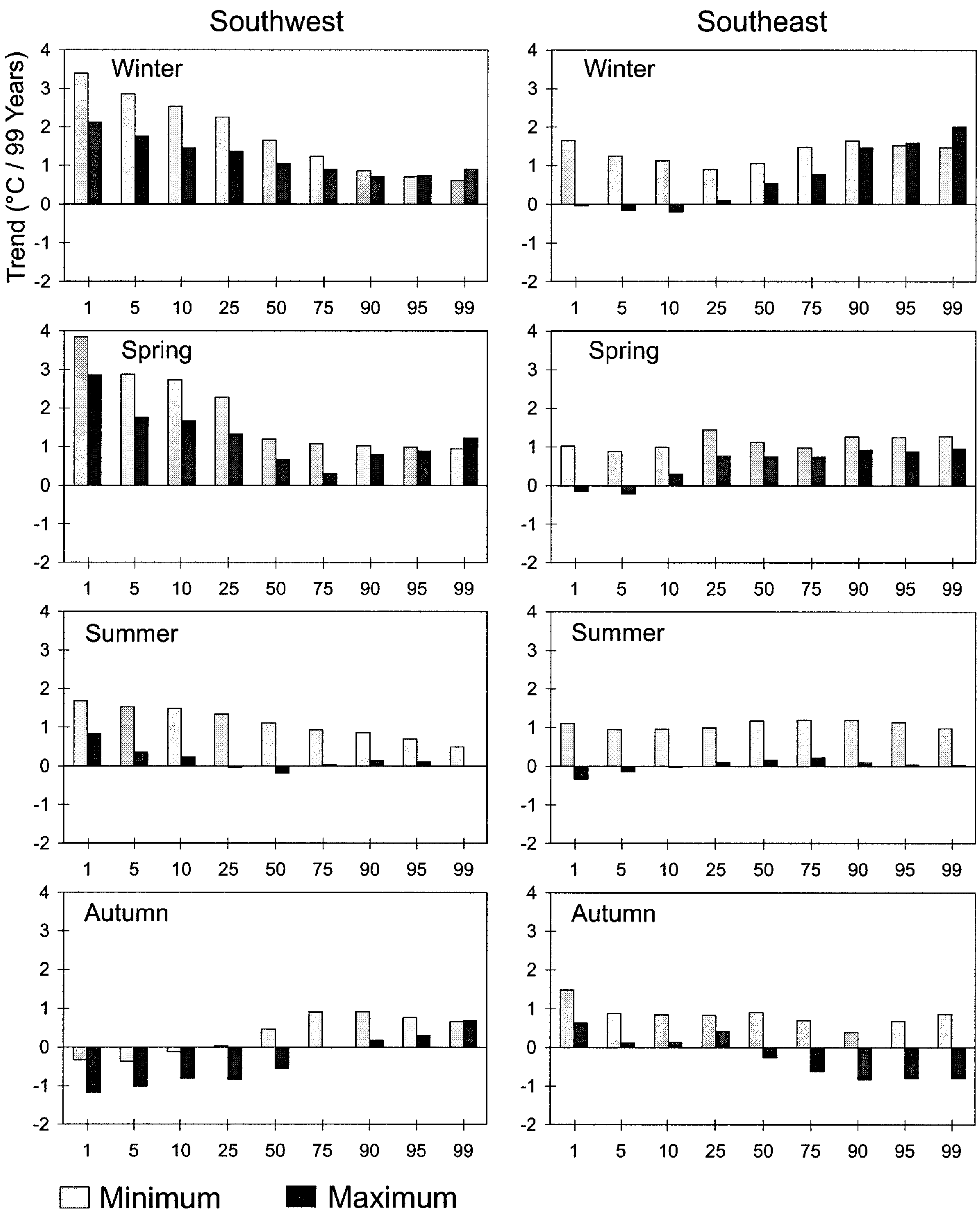

Fig. 7. Seasonal trends in various percentiles of daily minimum and maximum temperature over southwestern and southeastern Canada from 1900 to 1998 [°C (99 yr)$^{-1}$]. Note that the x axes are not to scale.

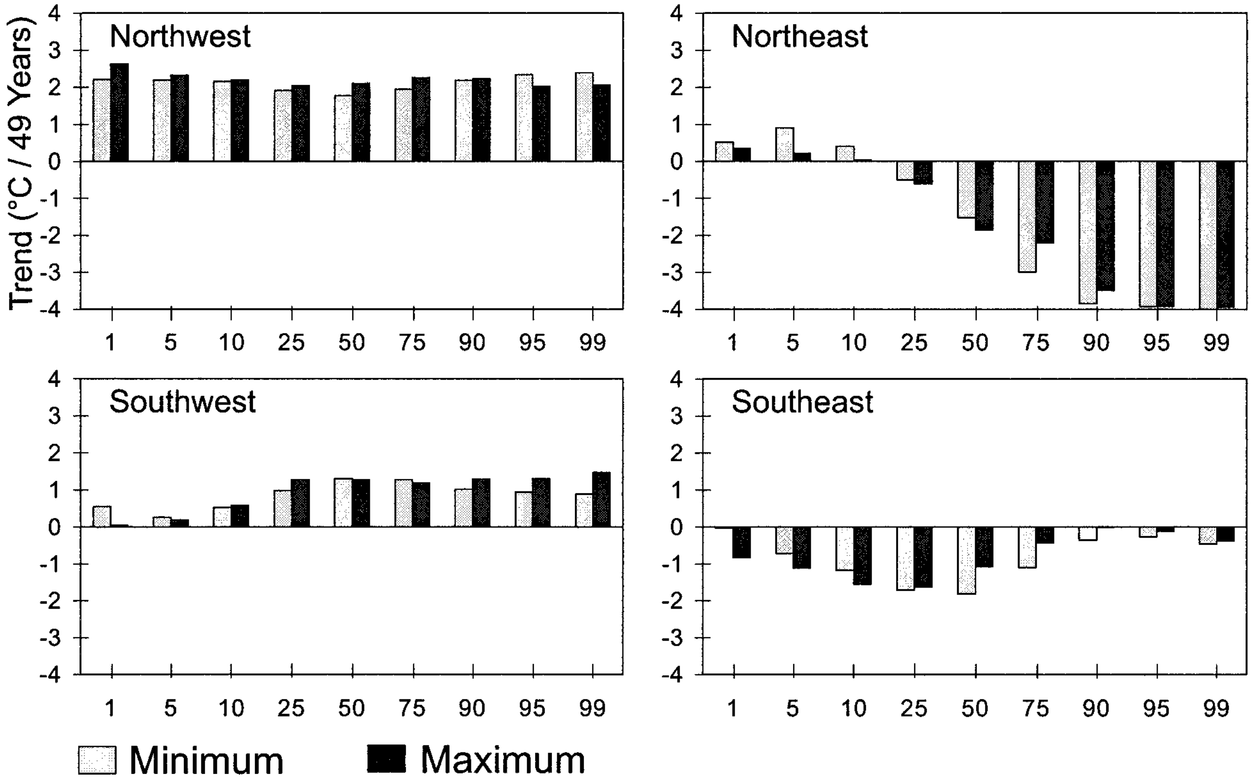

FIG. 8. Same as Fig. 7 but for winter trends from 1950 to 1998 over northwestern, northeastern, southwestern, and southeastern Canada [°C (49 yr)$^{-1}$].

southeastern (same as the previous), northwestern, and northeastern Canada. The last two areas are defined as all stations north of 60°N and west (east) of 85°W, respectively. As with the entire century, distinct regional characteristics in seasonal trends are observed from 1950 to 1998 (particularly, during winter and spring). Only winter plots are shown (Fig. 8), because they tend to display the greatest differences both regionally and with respect to the 1900–98 period (although other seasons are discussed). Over southwestern Canada, there have been increases to the higher percentiles for both daily minimum and maximum winter values but little change to the lowest percentiles. The trends on the left-hand side of the distribution in Fig. 8 are substantially different from those during the entire century (Fig. 7). Unlike winter, the general shape of the southwestern plots during the other three seasons (not shown) are very similar to those in Fig. 7. Southeastern winter trends in Fig. 8 are very different from those during the entire century (as well as, those over the southwest from 1950 to 1998) in that all percentiles have cooled. The decreases are slightly stronger for the left-hand side of the distribution and accounts for the observed increases in intraseasonal standard deviation during this period. Spring displays even stronger cooling in the lower percentiles of daily minimum and maximum temperature over the southeast (near −3°C). This is considerably different from southwestern Canada, where lower percentiles have increased by as much as 5°C (see Fig. 3b).

Northwestern Canada experienced a fairly uniform increase of about 2°–3°C to all percentiles of daily minimum and maximum winter temperature. The increase is larger in comparison with southwestern regions and agrees with the strong winter and spring warming that has occurred over the northwest during the second half of this century (Zhang et al. 2000a). Spring, summer, and autumn trends over the northwest are almost identical to those over the southwest for all percentiles (Fig. 7). Northeastern areas have a substantially different winter pattern from the rest of the country. Specifically, the higher percentiles have shown strong cooling (−4°C) while the lower experienced very little change. This signifies that the majority of the significant winter cooling over northeastern Canada is attributable to large decreases in the number of days with extreme high daily minimum and maximum temperature. The other three seasons (not shown) indicate smaller changes, including a uniform cooling to all percentiles of around −1° to −2°C during spring and relatively no changes to any percentiles during summer and autumn. For every season, the 1950–98 percentile trends are virtually identical between daily minimum and maximum temperature (see Fig. 8), unlike those observed, at least in the south, over the longer period (Fig. 7). These small differences are

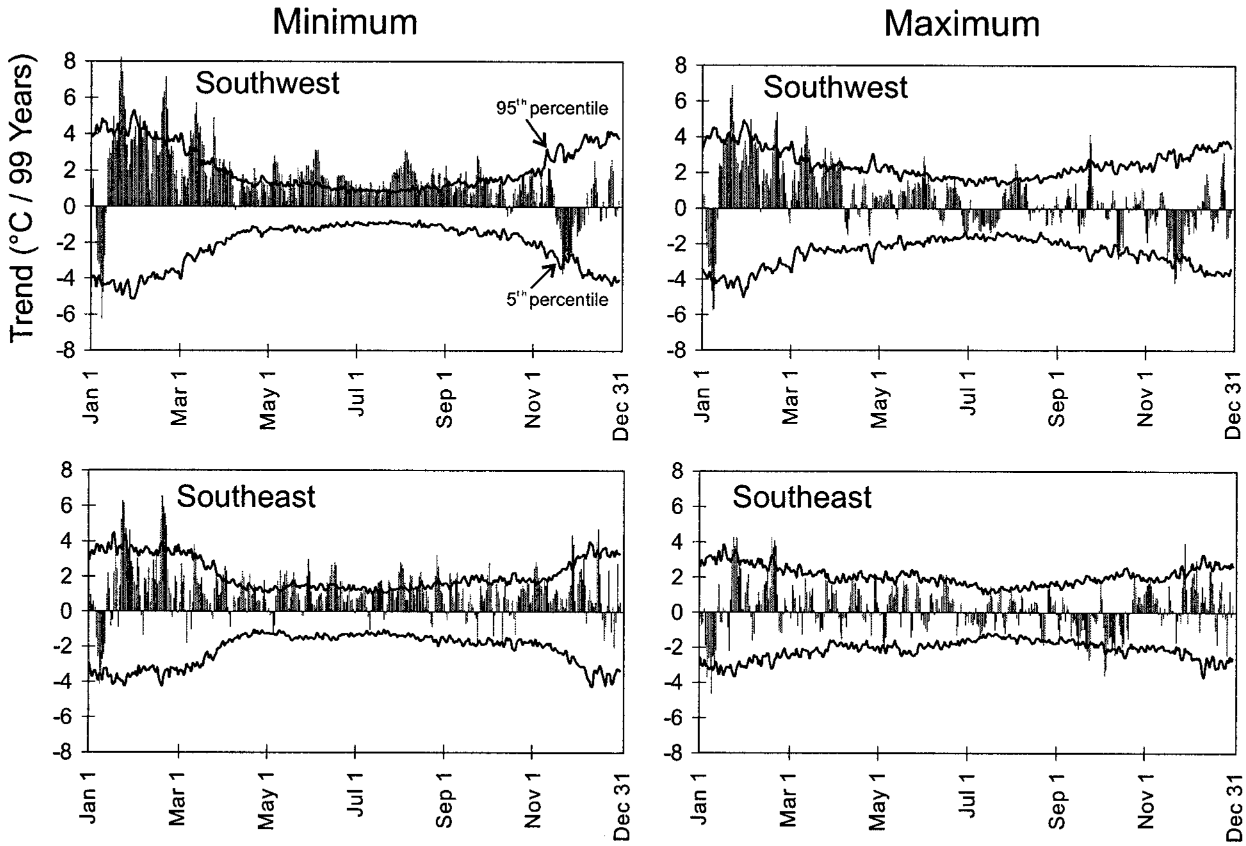

FIG. 9. Trends in daily minimum and maximum temperature over southwestern and southeastern Canada from 1900 to 1998 [°C (99 yr)$^{-1}$]. The 5th and 95th percentiles of the trends (as calculated by a permutation procedure involving 1000 random simulations) are also provided (see text for details).

consistent with the finding that DTR has not significantly changed during the second half of the twentieth century (Zhang et al. 2000a).

Twentieth-century temperature changes are further analyzed by examining regional trends in daily minimum and maximum temperature for every day of the year (Fig. 9). The significance of these trends is assessed using a permutation procedure similar to that described for Fig. 5. In this case, daily minimum and maximum temperatures for every station are randomly shuffled (for the 99 yr) for each of the 365 days so that the annual values are randomly ordered. Intra-annual variability and spatial relationships are retained by shuffling the values for each day and station in the same manner. Note that, for the warm part of the year (April–September), the January–December definition of a year is used in the permutation procedure. The cold part (October–March) incorporates the July–June definition. The procedure is repeated 1000 times, and the 5th and 95th percentiles of the trends are calculated for every day of the year.

Figure 9 shows that, over southern Canada, minimum temperature has generally warmed during the entire year, but increases to maximum temperature are confined to winter and early spring. In fact, over the southwest, positive trends in minimum temperature occur for a continuous period from near mid-January to the beginning of November. These trends exceed the 95th percentile during 43% of days within the year. On a seasonal basis, spring and summer show the greatest significance, with the 95th percentile being exceeded during 52% and 83% of the days within these seasons, respectively. Even though winter has the largest magnitude trends, relatively fewer days (19%) are significantly higher than the 95th percentile. This is likely attributable to the high degree of variability associated with winter temperatures over this region. Most of the autumn warming occurs during September and October. November is associated with several negative values. Minimum temperature trends over southeastern Canada are not as strong as those over the southwest. The 95th percentile is exceeded during 23% of the days within the year with the greatest significance also occurring in spring and summer. Unlike the southwest, late autumn is not associated with any cooling trends in minimum values. For maximum temperature, trends over southwestern Canada exceed the 95th percentile during 10% of the days within the year (majority during winter and spring). Southeastern maximum temperature trends reveal less warming with only 6% of days during the year exceeding the 95th percentile. As opposed to the southwest, the majority of these significant trends occur during only the winter season.

The trends in Fig. 9 also provide an indication into changes in the seasonal cycle of temperature over Canada. In particular, they suggest an earlier spring, especially, in the southwest. This is consistent with the significant trends toward an earlier breakup of river ice and ensuing peak flow observed over most of southern Canada during the last 50 years (Zhang et al. 2000b). In southwestern regions, autumn appears to have become shorter. This is due to the early part of the traditional autumn season (September) having warmed while the later part (November) has cooled. Note that all plots in Fig. 9 display a curious drop in daily temperature trends near the beginning of January. Values over the southwest show as much as a 5°–6°C cooling for minimum and maximum temperature (which is significantly lower than the 5th percentile). Further analysis reveals that, for the majority of stations across the southern Canadian region, these strong decreasing trends occur during an 8 to 10 day period centered between 4–6 and 12–14 January. They then dramatically increase. Reasons for this are not clear; however, a similar consistent fluctuation between a late-January warming and an early-February cooling has been identified over central England (Folland et al. 1999). It was attributed to a climatological tendency toward strong westerly circulation in January and blocking conditions in early February. Additional investigation is required to determine if similar circulation tendencies exist over Canada during the early part of the year.

Another important indicator of climate change involves variability (e.g., Karl et al. 1999), which can be assessed on a variety of temporal scales (e.g., interannual vs intra-annual). Some insight into the intraseasonal component of daily temperature variability was alluded to previously when it was found that, during seasons when the lower percentiles increased more than the higher, decreases in standard deviation occurred (and vice versa). Another measure that is likely more representative of day-to-day temperature variability involves first differences (Karl et al. 1995) where for a given period, absolute differences between consecutive daily temperatures are averaged. This investigation examines seasonal trends in the first differences of daily mean temperature over Canada (not shown). Results for the period of 1900–98 indicate decreases in day-to-day temperature variability during winter, spring, and summer over the majority of southern Canada (stronger in southwestern regions). Even autumn (which has increasing trends in the standard deviation of daily minimum and maximum temperature over southwestern Canada) is associated with several significant decreases in day-to-day variability (although not as consistent as the other seasons). The 1950–98 trends show less spatial consistency; however, during winter and spring, areas that experience significant increases (decreases) to daily minimum and maximum temperature are associated with significant decreases (increases) in day-to-day temperature variability. It therefore appears that, in general, day-to-day temperature variability has decreased over most of southern Canada during the twentieth century. However, the high degree of spatial variability in the trends suggest that more detailed research is required.

c. Economically sensitive indices

The final aspect of this study relates trends in several economically sensitive, daily temperature indices to the observed changes in daily temperature over Canada. The indices are chosen based on their significance to economic and/or social aspects of the Canadian climate, and their compatibility to other regions of the globe. Selected examples are given in Figs. 10 and 11. The first set of indices (Fig. 10) involves degree days, which are based on departures of daily mean temperature from a temperature-constant representative of the application in question. The departures are summed (on a yearly basis) to determine the annual number of degree days. An important economic index includes growing degree days (GDDs), an indicator of crop viability. The temperature constant varies depending on the crop and region under consideration. This investigation uses mean daily departures above 5.5°C, which is the same as other Canadian studies (e.g., Hare and Thomas 1974). Both cooling degree days (CDDs) and heating degree days (HDDs) are used to evaluate energy demand and consumption. Each incorporate the constant temperature of 18°C; however, the former represents departures above this value and the latter departures below 18°C. Trends in the length and start/end dates of the frost-free period are shown in Fig. 11. This interval is defined as the period during which minimum temperature remains above 0°C (i.e., number of days between the last spring and first autumn frosts) and can affect various activities such as agriculture, shipping, streamflow, and so on.

All trends in Figs. 10 and 11 are consistent with the observed changes in daily temperature shown previously. In particular, both GDDs and CDDs have significantly increased over most of the country during the entire and second half of the century. This is mainly attributable to increases in daily minimum (and thus, mean) temperature during the late spring, summer, and early autumn (see Figs. 7 and 9). A decrease in HDDs occurs at every station over southern Canada for the period of 1900–98 (with the majority being statistically significant). The decreases are considerably stronger than the CDD increases and are directly the result of the large-scale winter and early-spring warming of minimum and maximum temperature. The shorter period also shows several significant decreasing trends in HDDs, but they are confined to western Canada. Northeastern regions are associated with significant increases

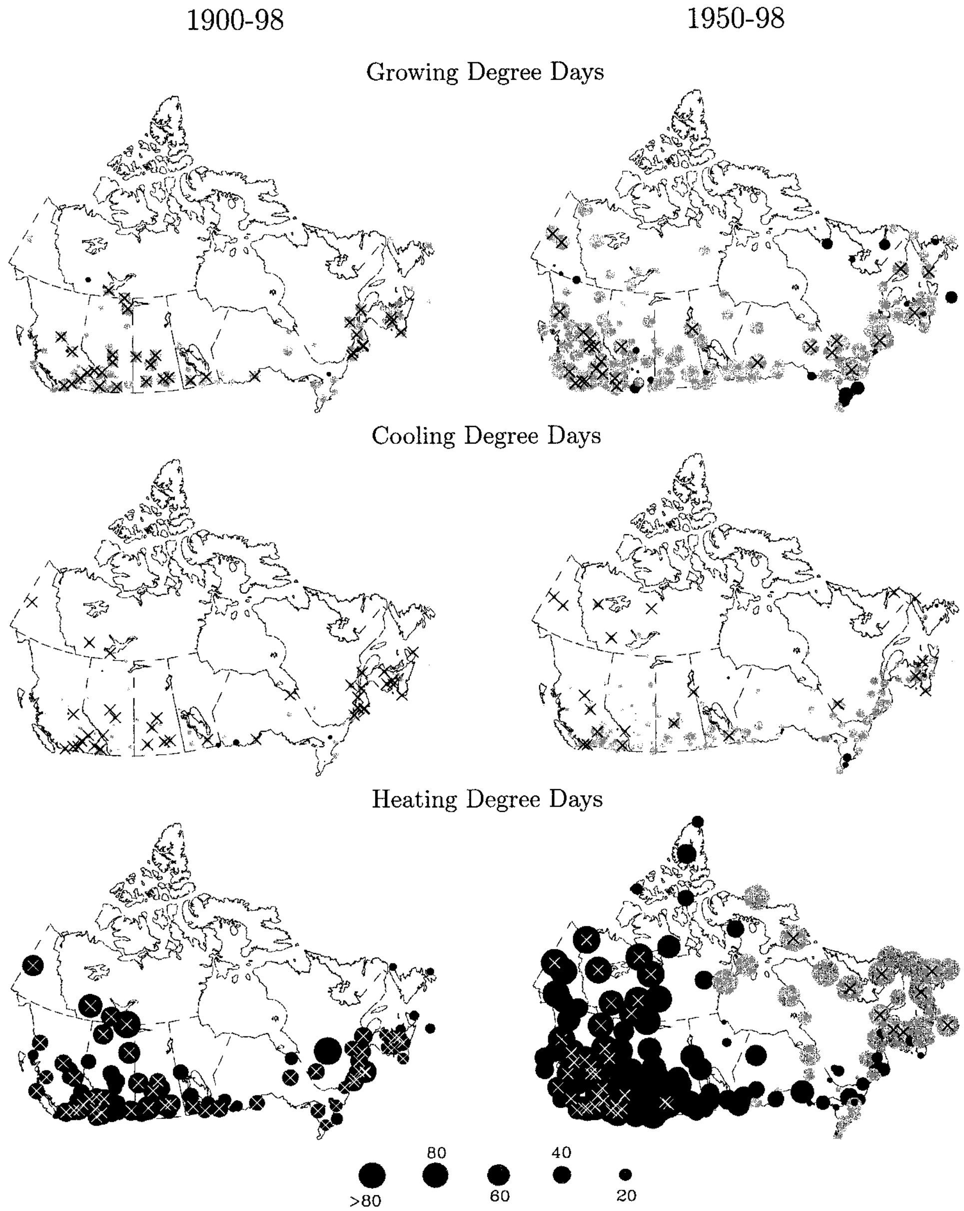

FIG. 10. Trends in the annual number of GDDs, CDDs, and HDDs from 1900 to 1998 and from 1950 to 1998 (degree days per 10 yr). Dots are scaled according to the amplitude of the trend, with light gray signifying positive trends and black signifying negative trends. Crosses denote trends significant at the 5% level.

due to the winter cooling observed over this area. The length of the frost-free period has significantly increased over most of the country (Fig. 11). This is due to a significantly earlier start and, to a lesser degree, later end to this interval (especially, from 1900 to 1998). The earlier start is consistent with Fig. 9, which suggests a shift toward an earlier spring over most of Canada. The trends toward later end dates during the entire century agree with the finding that the majority of autumn cooling has occurred later in the season (particularly, in the southwest; Figs. 7 and 9). By this time, it is well into the frost period over the majority of Canada. Trends in the length, start, and end of the growing season are also analyzed (not shown). This season is defined as the period during which the running 5-day daily mean temperature is maintained above 5.5°C (Bootsma 1994). Results are spatially and temporally similar to the frost-free period, although generally not as significant. Spring frost frequency (number of days minimum temperature falls below 0°C) has significantly decreased for the majority of stations during the entire and second half of the twentieth century (not shown). During autumn, sig-

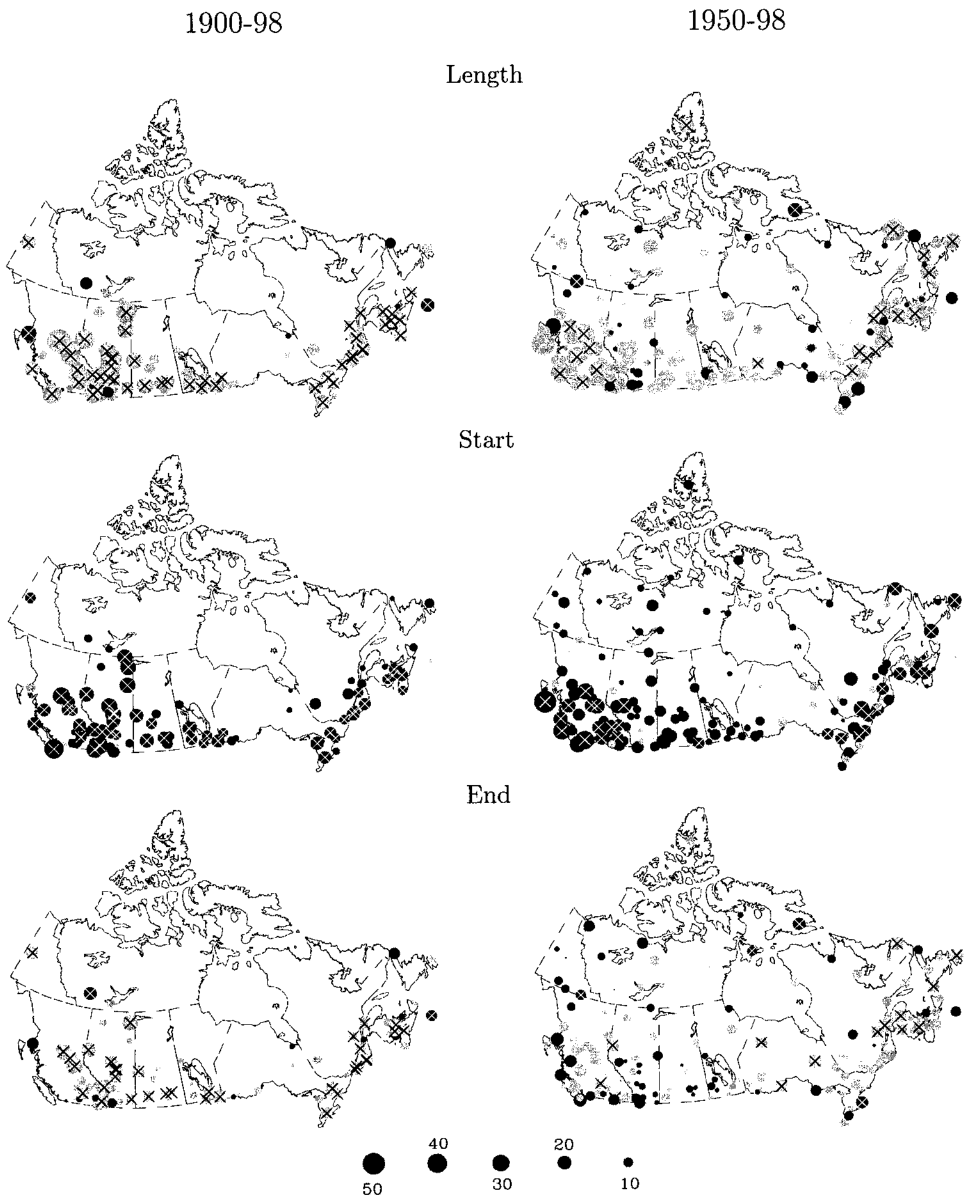

FIG. 11. Same as Fig. 10 but for the length, start, and end of the frost-free period. Units are number of days per 99 (49) yr, respectively. Light gray dots signify an increase in the length and a later start/end and black dots signify a decrease in length and an earlier start/end to the frost-free period.

nificant decreases in frost frequency are only observed from 1900 to 1998. Trends from 1950 to 1998 show regionally varying, insignificant values.

4. Summary and discussion

The preceding sections examine trends and variations in several daily and extreme temperature–related variables over Canada during the twentieth century. Results show considerable spatial, temporal, and seasonal variability, with the strongest and most significant trends tending to occur during winter and spring over western regions of the country. Analyses of low and high percentiles of daily minimum and maximum temperature indicate that, from 1900 to 1998, most of southern Canada is associated with significant trends toward fewer days with extreme low temperature during winter, spring, and summer. There are also trends toward more days with extreme high temperature in winter and spring, but these are not as pronounced as the decreases to extreme low values. There is no indication of any consistent changes to the magnitude of extreme high daily maximum temperature during summer, although substantial interdecadal variability is observed (Fig. 4). Extreme temperature–related trends from 1950 to 1998 display greater regional differences, mostly, during winter and spring (Figs. 3 and 8). This includes significant increases to low and high percentiles of daily minimum and maximum temperature over the west and significant decreases over the east. Summer has less spatial variability, with both lower and upper percentiles of daily minimum temperature significantly increasing over most of the country. Once again, there is no consistent trend in the higher percentiles of summer daily maximum temperature except for a few northern stations where significant increases are evident.

Results from the daily temperature analyses corroborate those of annual and seasonal temperature (Zhang et al. 2000a) in that they strongly suggest Canada is not getting hotter, but rather ''less cold.'' In particular, there has been a greater increase in daily minimum (as opposed to maximum) values (Figs. 7 and 9) and the largest warming has occurred during winter and early spring. Increases during summer have only been observed for minimum temperature. This study also reveals substantial regional and seasonal variability in the various percentile trends of daily minimum and maximum temperature (Figs. 7 and 8). Of particular interest is that over the southwest for both minimum and maximum values the left-hand side of the distribution has increased at a greater rate than the right-hand side during the entire twentieth century (with the exception of autumn). This has resulted in significant decreases in the standard deviation of daily temperature during these seasons. Several studies, including those incorporating GCMs, have suggested that relatively small changes in mean temperature could result in substantial changes to extremes (i.e., temperatures at the tails of the distribution), assuming the variance remains constant. However, as discussed previously, the variance of daily temperature has significantly decreased over many regions of the country. More detailed analyses regarding relationships among changes to the mean, extremes, and variance of Canadian daily temperature are required.

The Canadian temperature results shown here are similar to those over other regions of the globe. In particular, trends toward fewer days with low extremes have been observed over the United States (DeGaetano 1996; Karl et al. 1996), Great Britain (Jones et al. 1999), northern and central Europe (Brazdil et al. 1999), China (Zhai et al. 1999), and Australia and New Zealand (Plummer et al. 1999). For the majority of these regions, there were no increases to the number of days with extreme high summer maximum temperature, with some areas even showing decreases (e.g., Rohli and Keim 1994; DeGaetano 1996; Zhai et al. 1999). This has resulted in a decrease in day-to-day temperature variability over many areas of the world. Trends in economically sensitive indices (section 3c) are also consistent with those observed over various other regions. Examples include significantly longer growing seasons and frost-free periods over the northeastern United States (Cooter and Leduc 1995) and decreases in the number of frost days over Australia, China, northern and central Europe, New Zealand, and the United States (Easterling et al. 2000).

Many of the observed trends in this study are likely related to the increase in global mean temperature since the late-nineteenth century. The trends toward fewer days with extreme low minimum temperature are also consistent with the IPCC Second Assessment Report (Kattenberg et al. 1996), which stated that this kind of response should be expected in a warmer world. However, the IPCC projection of increases in days with extreme high summer temperature has, at present, not been observed over Canada. The extreme temperature findings are similar to recent transient greenhouse gas and aerosol simulations (Kharin and Zwiers 2000), which predicted increases in return values of daily minimum temperature to be substantially larger than those for maximum over land regions of the globe. The model also projected increases to extreme daily maximum temperature return values over central North America (including portions of southcentral Canada), which are not detected in this investigation. It is apparent that certain trends in extreme temperature variables over Canada are consistent with expectations for greenhouse gas–induced climate change, while others (e.g., trends in summer maximum values; the considerable spatial and temporal variability) suggest that other mechanisms are also at work (or perhaps, the models are not capturing the physical mechanisms responsible for the observed changes).

The majority of this analysis focuses on linear trends for the periods of 1900–98 and 1950–98. Examination of century-long time series (Figs. 4 and 5) reveals considerable decadal-scale variability, particularly, for extreme high summer temperatures. Causes for these decadal variations are beyond the scope of this investigation but may be related to factors such as cloud cover (e.g., Henderson-Sellers 1989) or large-scale oscillations including El Niño–Southern Oscillation, the North Atlantic oscillation (NAO), the Pacific Decadal oscillation, or the Arctic oscillation. The significant winter cooling over northeastern Canada during the second half of the century was significantly influenced by decadal-scale trends and variability in a NAO-related pattern (Shabbar et al. 1997). It is likely that many of the 1950–98 trends were at least partially affected by large-scale oscillations, and therefore their relationships to anthropogenic forcings remain uncertain. Further research into the attribution of the observed regional trends and variability of daily and extreme temperature over Canada is needed. Analyses of other climate parameters such as precipitation extremes, drought indices, and so on would also provide a better overall understanding of past changes and variability in the Canadian climate.

In conclusion, this study improves our knowledge regarding daily and extreme temperature trends and variability over Canada during the twentieth century. The majority of results are consistent with the expectations of a warming climate except for the lack of changes to extreme high summer temperatures. At this point in history, the observed warming appears to have had beneficial impacts that include a longer frost-free period, more GDDs, and fewer HDDs. However, the daily trends in Fig. 9 signify changes to the timing of temperature-related events (e.g., spring runoff, the skiing season, etc.). These changes could ultimately have adverse effects on various industries and on numerous environmental and ecological systems.

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