Temperature and Precipitation Trends in Canada During the 20th Century

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ABSTRACT *Trends in Canadian temperature and precipitation during the 20th century are analyzed using recently updated and adjusted station data. Six elements, maximum, minimum and mean temperatures along with diurnal temperature range (DTR), precipitation totals and ratio of snowfall to total precipitation are investigated. Anomalies from the 1961–1990 reference period were first obtained at individual stations, and were then used to generate gridded datasets for subsequent trend analyses. Trends were computed for 1900–1998 for southern Canada (south of 60°N), and separately for 1950–1998 for the entire country, due to insufficient data in the high arctic prior to the 1950s.*

From 1900–1998, the annual mean temperature has increased between 0.5 and 1.5°C in the south. The warming is greater in minimum temperature than in maximum temperature in the first half of the century, resulting in a decrease of DTR. The greatest warming occurred in the west, with statistically significant increases mostly seen during spring and summer periods. Annual precipitation has also increased from 5% to 35% in southern Canada over the same period. In general, the ratio of snowfall to total precipitation has been increasing due mostly to the increase in winter precipitation which generally falls as snow and an increase of ratio in autumn. Negative trends were identified in some southern regions during spring. From 1950–1998, the pattern of temperature change is distinct: warming in the south and west and cooling in the northeast, with similar magnitudes in both maximum and minimum temperatures. This pattern is mostly evident in winter and spring. Across Canada, precipitation has increased by 5% to 35%, with significant negative trends found in southern regions during winter. Overall, the ratio of snowfall to total precipitation has increased, with significant negative trends occurring mostly in southern Canada during spring.

Indices of abnormal climate conditions are also examined. These indices were defined as areas of Canada for 1950–1998, or southern Canada for 1900–1998, with temperature or precipitation anomalies above the 66th or below the 34th percentiles in their relevant time series. These confirmed the above findings and showed that climate has been becoming gradually wetter and warmer in southern Canada throughout the entire century, and in all of Canada during the latter half of the century.

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RÉSUMÉ *On a analysé les tendances de la température et de la précipitation au Canada durant le 20ème siècle en utilisant les données de stations récemment mises à jour et ajustées. On examine six éléments: les températures maximales, minimales et moyennes ainsi que l'écart diurne de température (EDT), la précipitation totale et le rapport neige à précipitation totale. On a d'abord obtenu les anomalies aux stations individuelles pour la période de référence 1961–1990, dont on a ensuite engendré des ensembles de données quadrillées utilisées pour les analyses de tendances. Les tendances ont été calculées pour 1900–1998 sur le sud du Canada (au sud de 60° de latitude nord) et séparément pour 1950–1998 sur tout le pays, à cause de l'insuffisance des données sur l'Arctique septentrional avant les années de 1950.*

De 1900 à 1998, la température annuelle moyenne a augmenté entre 0.5 et 1.5°C dans le sud. Le réchauffement est plus marqué pour la température minimale que pour la température maximale durant la première partie du siècle, ce qui diminue aussi le EDT. Le réchauffement le plus important s'est produit sur l'ouest, et on y voit des augmentations statistiquement significatives surtout durant les périodes de printemps et d'été. La précipitation annuelle a aussi augmenté de 5 à 35% sur le sud du Canada durant la même période. En général, le rapport neige à précipitation totale a augmenté surtout à cause de la précipitation hivernale, qui tombe principalement sous forme de neige, et aussi à une augmentation du rapport en automne. On a identifié des tendances négatives sur certaines régions du sud au printemps. De 1950 à 1998, le genre de changement de température est distinct: réchauffement sur le sud et l'ouest et refroidissement au nord-est, avec des amplitudes semblables pour les températures maximales et minimales. Ces caractéristiques se manifestent surtout en hiver et au printemps. Sur l'étendue du Canada, la précipitation s'est accrue de 5 à 35%, mais on trouve des tendances négatives sur les régions du sud en hiver. Dans l'ensemble, le rapport de la précipitation nivale à la précipitation totale a augmenté, mais avec des tendances négatives statistiquement significatives surtout sur le sud du Canada au printemps.

On examine aussi des indices de conditions climatiques anormales. On a défini ces indices comme les régions du Canada pour la période 1950–1998, ou du sud du Canada pour la période 1900–1998, démontrant des anomalies au dessus du 66ème ou sous le 34ème pourcentile de leur série temporelle propre. Ces indices ont confirmé les résultats ci-haut et montré que le climat est graduellement devenu plus chaud et qu'il y a plus de précipitations au sud du Canada tout au long du siècle, ainsi que partout au Canada durant la deuxième moitié du siècle.

1 Introduction

Recent analyses of climate trends indicate that the global mean surface temperature has increased by about 0.3 to 0.6°C since the late 19th century, and by about 0.2 to 0.3°C over the last 40 years (e.g., Nicholls et al., 1996). These studies have also shown that daily minimum temperatures have often increased at a greater rate than maximum temperatures, resulting in a decrease in the diurnal temperature range (DTR) for several regions of the world. There has been a small positive trend in global precipitation, of about 1% during the 20th century over land, with a greater increase in the high latitudes of the Northern Hemisphere, especially during the cold season. Considerable spatial and temporal variations have occurred over the past 100 years, and these tendencies of warming, increased precipitation and reduction of DTR have not been globally uniform. For example, Nicholls et al. (1996) showed warming in the mid-latitude Northern Hemisphere continents in winter and spring, and year-round cooling in the northwest North Atlantic and mid-latitudes over the North Pacific in the past four decades. Understanding the observed climate trends for Canada in terms of regional characteristics and hemispheric perspectives is important to assess regional changes and to understand further the global climate system. As well, the anthropogenic climate change signal is projected to be stronger in the high-latitudes (Nicholls et al., 1996). This suggests that it might be easier to detect climate change in a country like Canada.

The detection of climatic trends, including those predicted to occur from rising concentrations of atmospheric greenhouse gases (Wigley and Barnett, 1990), may be sought in historical climate records providing that such records are representative and cover a long enough period of time (typically more than 100 years). A number of data-related difficulties arise when attempting to analyze Canadian climate trends. Firstly, because of its vast land mass and location in high latitudes, the country experiences many different types of climate and relatively large spatial variability (Phillips, 1990). This requires a proper identification of the climate change signal from very noisy fields. Secondly, the observational network was not established in the north until the late 1940s and is very sparse. Thirdly, there have been changes in station location, in instrumentation and in observing practices which have caused inhomogeneities in the climatological records. Reliable trend estimates cannot be made before these inhomogeneity issues are adequately resolved. Many of these data-related issues have been addressed in Vincent (1990) and Gullett et al. (1992) for temperature records. Preliminary trend analysis was performed based on these datasets (Boden et al., 1994; Environment Canada, 1995; Skinner and Gullett, 1993; Gullett and Skinner, 1992). In these studies, seasonal and annual trends computed for maximum, minimum and mean temperatures for 11 climate regions established that significant warming has occurred in western Canada during the past 100 years.

Precipitation trend analyses were also reported in Boden et al. (1994) and by Environment Canada (1995). The data used in these studies were raw archive records, and hence were not rigorously assessed for temporal homogeneity. Results showed small increasing trends in the eastern part of the country over the period 1948–92, and they also indicated that precipitation in many regions has been below average since the mid-1980s. Groisman and Easterling (1994) identified some problems in Canadian precipitation data. Prior to trend computation, they adjusted monthly rainfall data before 1975 by a factor of 1.025 to account for temporal inhomogeneity caused by a gauge change that occurred in the mid-1970s. It was found that over the 1950–1990 period, both annual snowfall and total precipitation have increased by about 20% in northern Canada (north of 55°N), and that total precipitation has also increased in the southern part of the country. Precipitation data are more problematic compared with temperature data; Mekis and Hogg (1999) have shown that, due to cumulative daily problems such as wetting loss, evaporation and trace measurements in the Canadian data, it is difficult, if not impossible, to correct Canadian precipitation data on a monthly basis and that the Groisman and Easterling (1994) adjustment needed to be improved.

Since the early computations of trends in Canadian temperature and precipitation, data have been substantially improved and updated. A recently developed technique has made it possible to address better the homogeneity problems caused by changes in the station location and/or measurement programs in temperature records (Vincent, 1998). As well, a new temperature database which includes monthly mean maximum and minimum temperatures at 210 stations has been created (Vincent and Gullett, 1999). Comprehensive adjustments of daily rainfall and snowfall have been performed for known changes of instruments, as well as for gauge undercatch, wetting loss and trace measurements (Mekis and Hogg, 1999) for about 500 stations. The computation of trends has also been improved. It is recognized that autocorrelation is quite common in temperature and precipitation time series, and may affect the linear trend computation (e.g. von Storch, 1995). Autocorrelation, a factor that was not taken into account in any of the previous studies, has been considered in this analysis.

Different components of the climate system interact and changes in one element can affect others. For example, warming in minimum temperature over global land surfaces is almost three times the magnitude of that for maximum temperature during 1951–1990 (Karl et al., 1993a). This was likely caused by changes in global cloud cover, and resulted in a decrease in the DTR. The outputs from simulations by three General Circulation Models (GCMs) for double CO_2 showed that a significant increase in snow accumulation in the arctic region is expected as a result of global warming (Ye and Mather, 1997). These examples suggest trends be analyzed on multiple variables. Providing trends in the most important climate variables for Canada is therefore a major objective of this study. We will present spatial distributions of trends along with their statistical significance for the following six elements: maximum, minimum and mean temperatures; DTR; precipitation totals and the ratio of snowfall to total precipitation.

In an effort to provide a set of indices which represents complicated multivariate, multidimensional climatic changes that can be readily understood and used by policy makers, Karl et al. (1996) developed and analyzed a climate extremes index (CEI) and a greenhouse climate response index (GCRI) for the United States. They found a positive trend in the U.S. GCRI during the 20th century that is consistent with projections resulting from increased emissions of greenhouse gases. The computation of similar indices such as indices of abnormal climate for Canada (to be defined in the next section) will provide a comparison with those computed for the U.S., and may also be used to verify the results of trend analysis. A preliminary examination of time variations of indices of abnormal climate is another objective of this study.

Due to the limited data availability in northern Canada prior to the 1950s, two periods have been analyzed in this study: 1900–1998 for southern Canada (south of about 60°N), and 1950–1998 for Canada as a whole (Fig. 1). After the description of data and methodologies used in Section 2, we will present temperature and precipitation trends during 1900–1998 for southern Canada and during 1950–1998 for the whole of Canada in Sections 3 and 4, respectively. The indices of abnormal climate which are similar to the GCRI of Karl et al. (1996) are examined in Section 5. Conclusions and discussion follow in Section 6.

Fig. 1 Major Canadian political boundaries with provincial and territorial names. The Canadian Prairies include the provinces of Alberta, Saskatchewan and Manitoba. The Mackenzie Basin is shaded. Southern Canada is the region south of the 60°N.

2 Data and methods

a *Data*

The basic data used in this study are from the recently created database of monthly temperature at 210 stations (Vincent and Gullett, 1999), and daily rainfall and snowfall at 489 stations (Mekis and Hogg, 1999). To facilitate analysis and interpretation, these datasets were first gridded, with a spatial resolution of 50 km on a polar stereographic projection, using the Gandin optimal interpolation technique (Milewska and Hogg, unpublished manuscript).

The temperature data are monthly means of daily maximum and minimum temperatures. The 210 stations are relatively evenly distributed across Canada (Fig. 2). Records from different sites were sometimes joined to extend temporally the series backward to maximize coverage during the 20th century. However, record lengths still differ from one station to another. These data have undergone rigorous quality control, and have been adjusted for identified inhomogeneities caused by station relocation, changes in instrumentation and in observing practices. A significant improvement over previous versions of the temperature database is the adjustment in the minimum temperature to account for changes in observing procedure at principal stations in 1961 (Vincent and Gullet, 1999). Adjustment for this bias results in a less pronounced cooling in minimum temperature in terms of magnitude (by as much as 0.5°C) and spatial extent in eastern Canada (Ontario, Quebec and the Atlantic provinces) during 1946–1998. The monthly mean temperature is derived from computing the average of the monthly maximum and minimum temperatures, while the monthly mean range was obtained by subtracting the monthly mean minimum temperature from the monthly mean maximum temperature. Seasonal and annual time series were calculated from the monthly values. The standard climatological seasons, i.e., December to February for winter, March to May for spring, June to August for summer, September to November for fall, were used in computing seasonal values.

Data collected from the 489 stations recording daily precipitation were also subjected to rigorous quality control. In addition to being strategically selected to cover as much of the country as evenly as possible, the data covered the period 1900–present. Based upon station history information, all known inhomogeneities in the precipitation time series resulting from changes in instrumentation or observing practices were carefully minimized. Wind undercatch and wetting loss were corrected according to different types of rain gauges. A 4% or 2% increase was added to observations to account for wind undercatch of the Meteorological Service of Canada gauge and the Type-B gauge, respectively. Trace events and spatially varying snow densities were also considered when adjusting the data. It is probable that trace events were not systematically reported/recorded throughout the century at all stations, but it was found that adjustment for trace events had little impact on trend computation. As a result, this dataset is the most homogeneous available and represents a significant improvement over other Canadian precipitation data. Mekis and Hogg (1999) detail the procedure and effects of the adjustment of precipitation data. Monthly, seasonal and annual totals of rainfall and snowfall were computed from daily amounts. The total precipitation was computed by summing the amounts of rainfall and snowfall, and the ratio of snowfall to total precipitation was also obtained.

The station data were gridded using a procedure developed by Hogg et al. (1997). The procedure uses statistical optimal interpolation and employs climatology as a "first guess" field and interpolating only the departures from the climatology of the relevant field. Hogg et al. (1997) demonstrated that this procedure is effective when interpolating monthly precipitation in data-sparse, strong-relief regions. Compared with the original field, the anomaly field is more homogeneous and isotropic and therefore better meets the essential requirements for proper statistical optimal interpolation. The interpolated anomaly grids were the basis of most of the analysis described here. Trends or abnormal climate indices were directly computed from gridded anomaly fields. Departures from the reference period 1961–90 were first calculated at individual stations. For precipitation, the anomalies were further normalized by dividing by the 1961–90 period means. These normalized anomalies were then interpolated to the grid using the Gandin Optimal Interpolation technique (Alaka and Elvander, 1971; Milewska and Hogg, unpublished manuscript). The anomalies of ratio of snowfall to total precipitation were also gridded.

The error of interpolation was assessed in a cross-validation framework. One station at a time was withheld and the remaining stations were used to generate gridded values. The station data were then compared with the values at the nearest grid. To make the cross-validation computationally manageable while providing reliable information on the quality of the gridded datasets, the cross-validation was performed on selected parameters and stations. It was carried out on seasonal time series for the period 1961–90 on maximum temperature at 59 stations, precipitation and the ratio of snowfall to total precipitation at 68 stations. The selected stations were evenly distributed across the country, including several in the data-sparse north. It is reasonable to assume that the other three temperature related elements – anomalies of minimum and mean temperature, and DTR – are as spatially homogeneous as the maximum temperature anomalies, and their gridded datasets should be of the same quality as the gridded maximum temperature anomalies. Figure 2 shows the root mean square errors (RMSE) between the anomalies of station data and the nearest grid point. The average RMSE seasonal mean maximum temperature is 0.47°C with smaller values (typically between 0.2–0.4°C) in southern Canada where the observational network is denser. On average, this RMSE is about 0.26 standard deviations of the seasonal mean maximum temperature. The correlation coefficients for temperatures at grid and station are generally larger than 0.95 in southern Canada, and larger than 0.85 in the northern part of the country. These coefficients indicate that the optimal statistical interpolation technique performed reasonably well for the temperature data even in the very remote and data-sparse area. It may be concluded that the anomalies of maximum temperature provide a reasonably homogeneous field.

The RMSE for normalized seasonal precipitation anomalies is also shown in Fig. 2. The average RMSE is 0.23 (or 23% of the mean) with errors less than 0.2 (20%) in the southern part of the country. This translates to about 0.5 standard deviations. The grid to station correlation coefficients are generally not as high as those for temperature; nevertheless, given the spatial variability of the element, the interpolation was considered to be satisfactory. The correlation coefficients for the ratio of snowfall to total precipitation were much higher than those for precipitation anomalies, which indicates that this ratio is more homogeneous than the precipitation anomaly field.

The interpolation procedure plays the role of a spatial filter and thus removes local noise to some extent. The gridded fields are smoother than the station data and are more suitable for describing large-scale features such as long-term trends. To reduce the amount of calculation, trend analysis was performed on the time series of a coarse 200 × 200 km grid obtained by averaging the values of 16 grid points from the 50 × 50 km grid. This procedure further smoothes the fields. Since the climate observation network was not established in northern Canada until the late 1940s, there were large portions of the country with no data during the first half of the century. Based loosely on error analyses reported in Milewska and Hogg (unpublished manuscript) and those reported here, interpolation limits were established. No more than five stations with the shortest distance (less than 750 km for precipitation and 1000 km for temperature) to a grid point are used to interpolate the value for the grid. The distance limits are seldom reached. For example, more than 80% of grid values for precipitation have stations within 200 km. No grid values were generated for northern Canada (north of about 60°N) prior to 1950s due to insufficient data. Trend analysis was performed on datasets for 1900–1998 for the southern part of the country (south of about 60°N) where grid values were complete for both temperature and precipitation, and for 1950–1998 for the nation as a whole.

b *Extreme and Abnormal Climate Indices*

Karl et al. (1996) used a set of indicators which represent a projected response of U.S. climate change caused by the increase of greenhouse gases in the atmosphere (e.g. Nicholls et al., 1996). These indicators include the percentages of the U.S. with much higher than normal (larger than 90th percentile) mean temperature, with much higher than normal precipitation during the cold season. Jones et al. (1999) have used similar indicators to determine the areas of the world affected by extreme temperature. A detailed investigation of all those indicators for Canadian climate merits a separate study. Here, we present some extreme climate indices such as extreme cold (dry) and warm (wet) indices. These are defined as percentages of the nation affected by extremely cold (dry) and warm (wet) conditions, respectively, and represent temperature (precipitation) below the 10th and above the 90th percentiles in the relevant time series. For example, for a particular year (season), the extreme dry index is obtained by counting the number of grids in that year (season) when the precipitation is below the 10th percentile and then dividing by the total number of grids. In many regions of Canada, climate does not need to be at an extreme to have severe impacts on environmental processes and economic activities like agriculture. For example, there is normally just enough precipitation to sustain agriculture, in the semi-arid regions of southwestern Saskatchewan and southern Alberta. Any departure from normal may have severe effects (Bonsal et al., 1999). Moreover, a combination of anomalies in different parameters, such as warm temperature with lack of precipitation, may have even more severe repercussions. It should be noted that extreme conditions occurring in several climate variables at the same time, such as precipitation and temperature, are rare; therefore, we also computed “abnormal” climate indices, defined similarly to those of extreme climate indices, with thresholds being the 34th and the 67th percentiles. Indices were then computed to represent the joint abnormal conditions in both precipitation and temperature.

c *Methods*

In most climate trend studies, it is generally assumed that the climate time series consists of a long-term trend component and a white noise residual component (Wigley and Jones, 1981). This assumption was used in previous studies of Canadian climate trends (e.g. Skinner and Gullett, 1993; Boden et al., 1994; Environment Canada, 1995). Most climate series, however, actually contain red noise and are serially correlated due to the multi-year nature of natural climate variability. Assuming white noise residuals will result in an overestimation of the effective sample size of the residuals (Leith, 1973; Trenberth, 1984), and hence overestimation of the significance of a trend (von Storch, 1995). To overcome such problems, recent approaches have introduced regression models with serially correlated residuals (Bloomfield, 1992; Bloomfield and Nychka, 1992; Woodward and Gray, 1993). Some studies have also included so called "explanatory variables" such as the southern oscillation index (Zheng et al., 1997; Zheng and Basher, 1998). Including explanatory variables in the equation will help to increase the fit of the model, but, this may also bias the magnitude of the trend since the explanatory variables themselves generally are not time independent and contain the signal of trend to be detected.

Climate trend at the regional scale is by no means easy to detect; regional climate has relatively greater variability associated with natural climatic processes. This, together with the relatively short periods of time of observations in Canada, interferes with the proper identification of statistically significant regional trends. In this study, we have attempted to produce more reliable estimates of the magnitude and the statistical significance of the trend. Since serial correlation in the climate time series can influence the estimate of trend, and that trend can in turn have an impact on computation of the serial correlation, we have investigated a new approach to obtain the linear change that takes the serial correlation into account. To accomplish this, we have used the following statistical model:

$$Y_t = \mu + T_t + \nu_t \tag{1}$$

where
Y_t is a climate variable at time t,
μ is the constant term,
T_t is the trend, and
ν_t is the noise at time t.
To simplify computation, the trend is assumed to be linear, i.e.,

$$T_t = \beta t \tag{2}$$

where β is the slope of the linear regression between the climate variable and time. The noise is represented by a pth order autoregression, AR(p),

$$\nu_t = \sum_{r=1}^{p} \phi_r \nu_{t-r} + \varepsilon_t, \tag{3}$$

where ϕ_r are the parameters of the autoregressive process and $\{\varepsilon_t\}$ is white noise.

The order of the autoregression p was determined by computing the autocorrelation and the partial autocorrelation functions of each climate element at individual grid points. The partial autocorrelation for lags larger than one is, in general, not significantly different from zero. Therefore, we used an AR(1) process to model the noise. Thus, equation 1 becomes:

$$Y_t = \mu + \beta t + \phi Y_{t-1} + \varepsilon_t \tag{4}$$

The following iteration procedure was used to estimate the parameters in equation

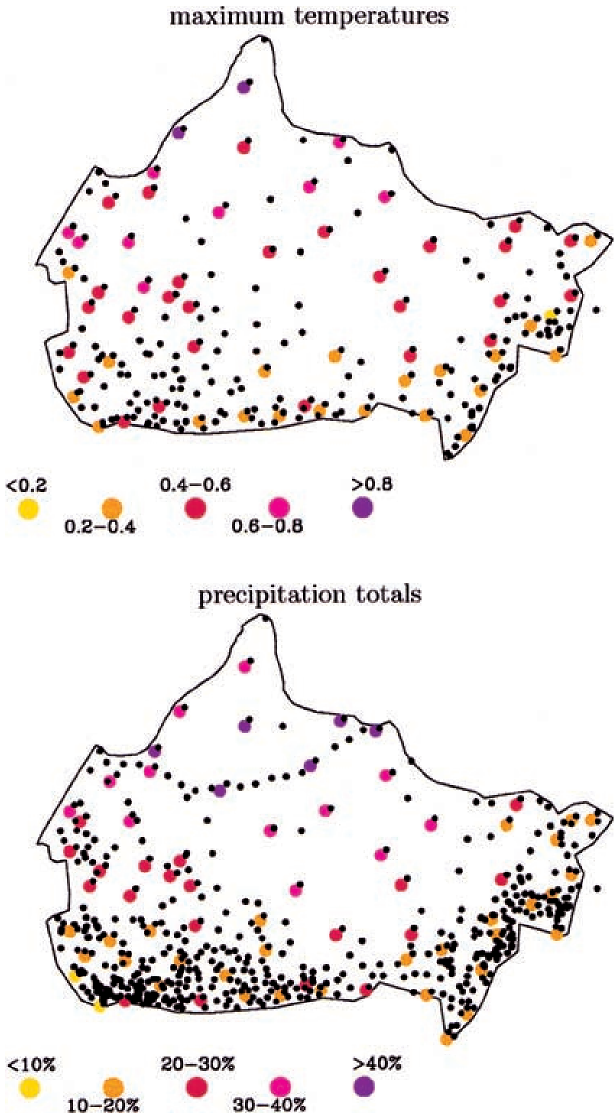

Fig. 2 Locations (black dots) of stations used for gridding (210 for temperature, 489 for precipitation). Coloured dots represent root mean square errors between anomalies of the station data and the nearest grid point at 59 grids for maximum temperature (upper panel, in °C) and at 68 grids for the precipitation totals (lower panel) during 1961–1990.

4. A first guess of ϕ is computed directly from the dataset, and is used to remove the autocorrelation from the time series. Then β and its significance level are obtained from the de-autocorrelated time series by computing a simple and robust estimator of β based on the non-parametric Kendall's rank correlation tau (Sen, 1968), or the median of the slopes obtained from all possible combinations of two points in the series. We have used the Kendall estimate instead of the least squares estimate because it is less sensitive to the non-normality of the distribution and less affected by extreme values or outliers in the series. Both conditions can often be found in climatological time series, and in particular, in precipitation datasets. The estimated β is then used to remove the trend from the original series and the resulting residuals are used to obtain a second and more accurate estimation of the lag-1 autocorrelation coefficient. Once again, the newly estimated ϕ is used to pre-whiten the original series and a second estimate of β is obtained. This procedure continues until the differences in the estimates of both β and ϕ in two consecutive iterations are small enough. The procedure usually converges within 3 to 12 iterations. Monte-Carlo tests involving 1000 simulations each for a variety of autocorrelation and trend combinations confirmed that our procedure does produce satisfactory results.

To determine the statistical significance of the trend, the confidence interval for the slope β is obtained in terms of lower and upper bounds based on the order of all possible slopes. This confidence interval is not sensitive to non-normality of the datasets, nor to outliers in the series. Using a limited number of series, we have compared the magnitude and statistical significance of the trend when the traditional linear model was fitted and when our approach was used. Generally, we have found that our approach produced a slightly smaller magnitude than that obtained by the traditional linear model, and, in some cases, trends identified as statistically significant using linear regression are not significant using our procedure due to positive autocorrelations in the time series. Throughout this paper, we use the 5% level to define statistically significant trend.

3 Trends for 1900–1998 (southern Canada)

a *Temperatures*

Based upon the gridded datasets, the time series of annual mean temperature anomalies relative to the 1961–1990 mean, are computed and shown for southern Canada (1900–1998) in Fig. 3. There is a statistically significant positive trend, which accounts for an increase of 0.9°C, for the region during the period. The linear trend is not exactly monotonic. The rises of temperature prior to the 1940s and after the 1970s account for the significant trend. There is a modest decrease during 1940–1970. Trends differ for different regions, and for different seasons, as well as for daily maximum and minimum temperatures.

Mapped trends in annual and seasonal mean daily maximum temperature are depicted in Fig. 4 for 1900–1998. The annual mean daily maximum temperature has increased since the beginning of this century in the southern part of the country. Statistically significant trends are observed in Alberta and Saskatchewan, as well as in

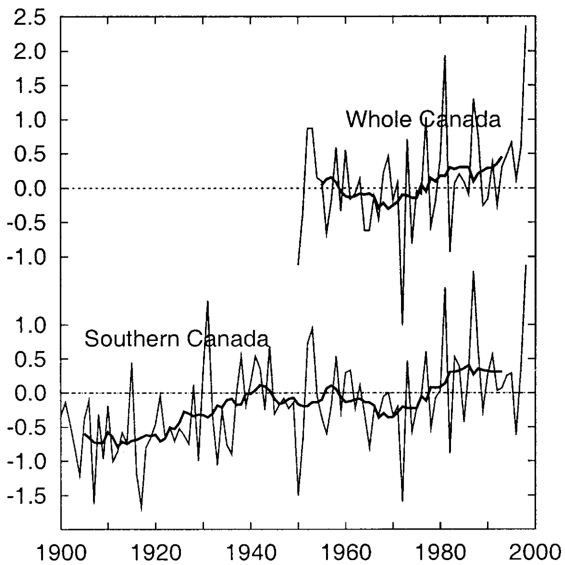

Fig. 3 Departures from the 1961–1990 mean of area average mean temperature (°C). Bold curves are 11-year moving averages.

eastern Quebec. The greatest warming, which is in the Prairies, is about 1.5°C over the 99-yr period. The spatial patterns of the trends differ from season to season. The mean daily maximum temperature has increased over all of southern Canada in both winter and spring. However, it has increased in some areas but decreased in other areas during summer and fall. Among the four seasons, spring shows the greatest warming. The spatial pattern in this season is similar to the annual one, except that spring warming is stronger and the area with significant upward trend has expanded from the Prairies to include northern B.C. and Manitoba. The greatest warming during spring is well over 2°C for the 1900–1998 period in the Prairies. Warming during winter is more than 1.5°C during 1900–1998 in western Canada, however, the trends are significant only in southwestern B.C. Summer maximum temperature shows significant positive trends in Quebec and the Prairies, and significant negative trends in southwestern B.C. Fall shows no significant warming or cooling trends. It is apparent that warming in spring maximum temperature contributed the most to the positive trend in the annual mean of daily maximum temperature.

Strong warming is the sole characteristic of the minimum temperature. This is clearly shown in Fig. 5, where no negative trends can be found. Annual mean minimum temperature has increased from about 1 to 2.5°C during the last 99 years, with strongest warming in the Prairies and southern Quebec. The trends are statistically significant over all of southern Canada. Spring minimum temperatures have warmed the most, with a rate over 3°C during 1900–1998 in the northern Prairies. Winter has

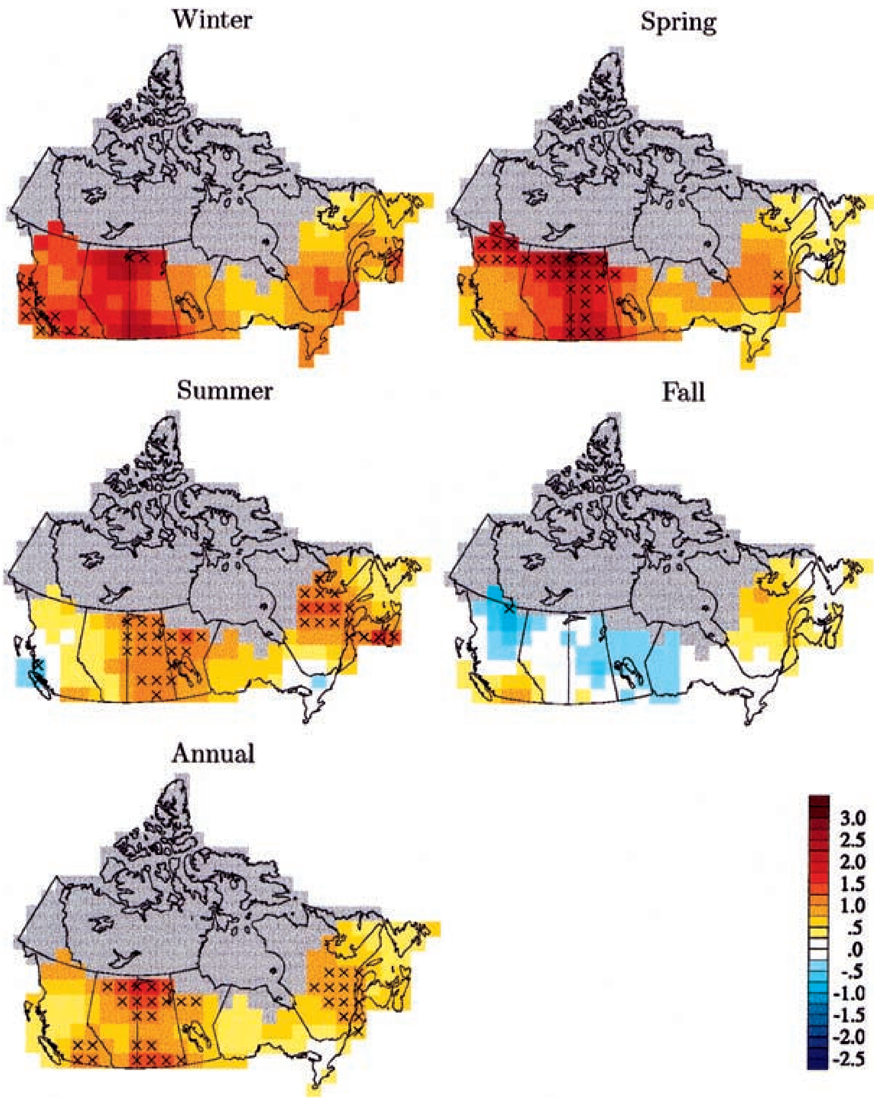

Fig. 4 Trends in daily maximum temperature from 1900–1998. Units are °C per 99-year period. Grid squares with trends statistically significant at 5% are marked by crosses. Grey areas indicate insufficient data.

the second highest warming rate with some areas in the Prairies and B.C. reaching as high as 3°C, however, some of the warming in Manitoba, Ontario and along the east coast is not significant. In summer, the spatial pattern is quite uniform with significant trends from 1.3 to 2.0°C. During the fall, the minimum temperatures have warmed with significant increase in eastern Canada and along the west coast. Overall, these results clearly show that daily minimum temperatures, indicators of night-time temperatures, have significantly increased throughout southern Canada over the past century.

Significant positive trends were also found in the annual and seasonal daily mean temperatures. The spatial patterns (not shown) are similar to those of minimum temperatures but the trends are of a lesser magnitude. This suggests that it is the strong and positive trends of the minimum temperatures, especially during spring and summer, that contributed the most to the trend in the mean temperatures. The annual mean temperatures have increased by about 0.5 to 1.5°C during the last 99 years over southern Canada, with the highest magnitude being a 1.5°C increase in the Prairies. The spatial distribution of trend in the annual mean temperature agrees well with those identified for the U.S. (Karl et al., 1996) across the Canada-U.S. border. In fact, except in the southeast U.S., which showed mostly cooling and the Canadian High Arctic where data were insufficient, North America has exhibited warming in annual mean temperature during the 20th century. The greatest warming has been in the Canadian Prairies extending to the central U.S. It appears that warming in southern Canada is a part of the larger mid-high latitude continental warming of North America.

The trends in annual and seasonal, maximum, minimum and mean daily temperatures confirm the results for climate regions in southern Canada reported in Environment Canada (1995) for the period 1895–1991. Although the time periods analyzed are not identical, both studies showed similar results.

Greater warming in the minimum than in the maximum temperatures results in significant decrease in the daily temperature range since the beginning of this century (Fig. 6). Significant decrease in the DTR is observed from coast to coast and for all seasons, with a trend of –0.5 to –2.0°C during 1900–98. We can conclude that night-time temperature has increased more than daytime temperature in all seasons in the southern part of Canada during the last century. Most of the decrease in the DTR occurred prior to the 1950s, especially late in the first half of the 20th century, coinciding with an increase in total cloud amount in Canadian mid-latitudes during the first half of the 20th century (Henderson-Sellers, 1989; McGuffie and Henderson-Sellers, 1988). Henderson-Sellers (1989) did not propose any specific reasons for the cloud increase. Significant decrease in the DTR did not occur in the second half of the century when the greatest increase in greenhouse gases took place. This suggests that trends in the DTR are closely related to changes in total cloud amount. The trends in both DTR and total cloud cover differ from one season to the other. Future investigation into the relationships between the changes in DTR and cloud cover is needed.

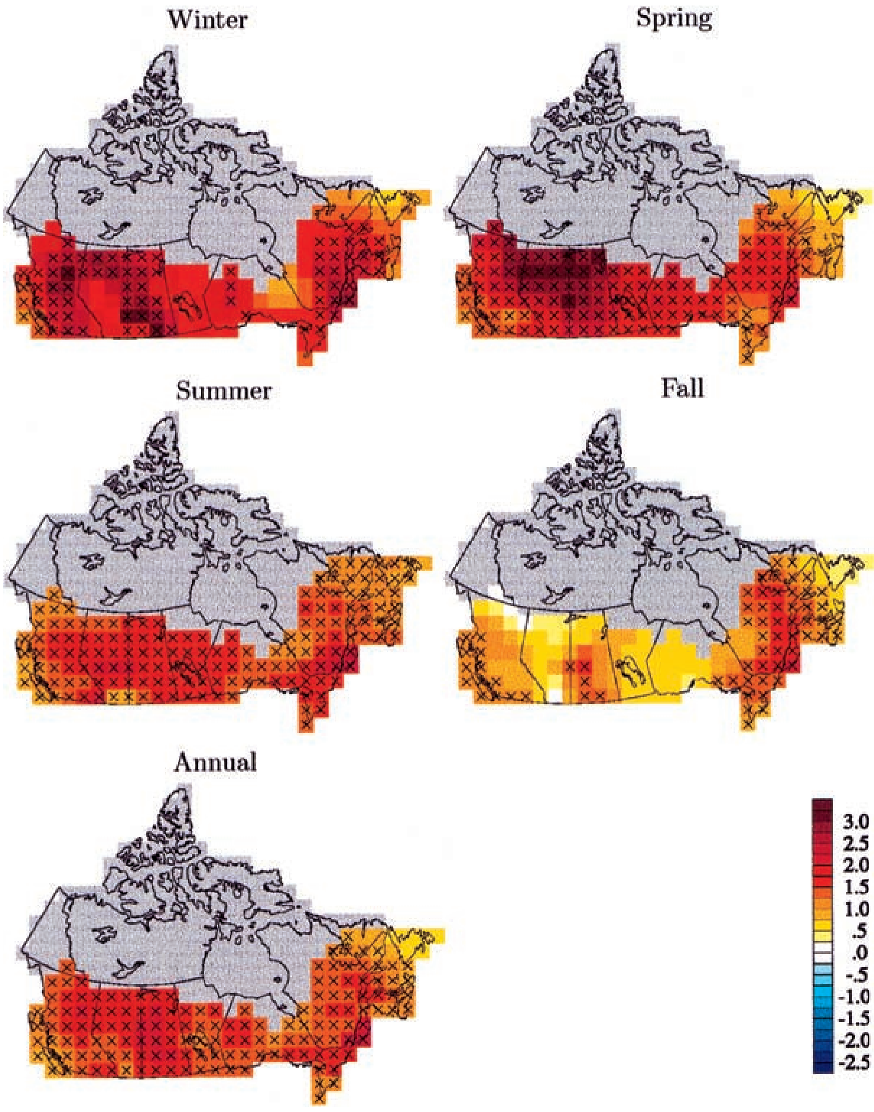

Fig. 5   As in Fig. 4, but for daily minimum temperature.

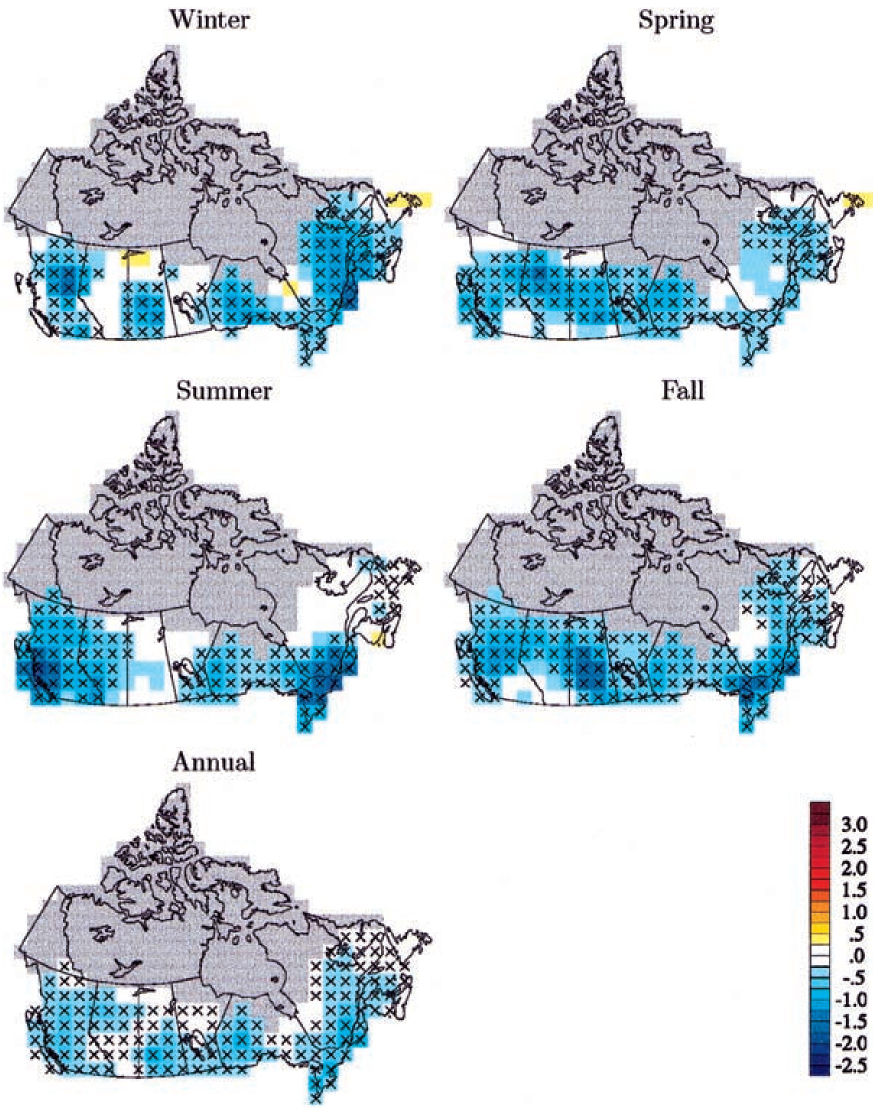

Fig. 6 As in Fig. 4, but for daily temperature range.

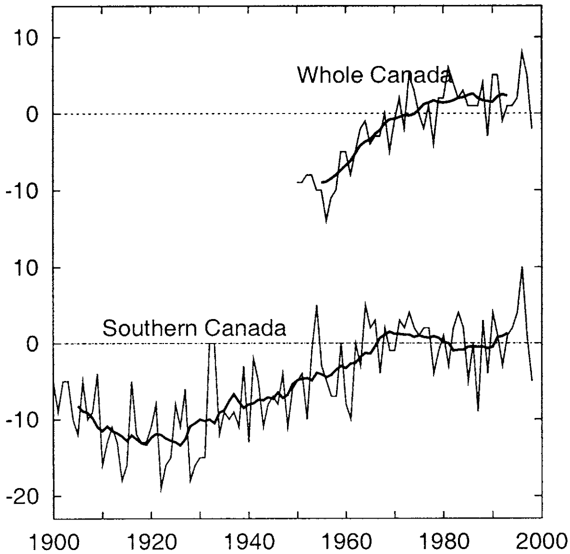

Fig. 7 Departures from the 1961–1990 mean of area average annual precipitation. The departures are the relative changes (in %) to the 1961–1990 mean. Bold curves are 11-year moving averages.

b *Precipitation*

Time series of precipitation anomalies (in percentages of 1961–90 mean) are displayed in Fig. 7. Annual precipitation increased by 12% in southern Canada during 1900–1998. The increase in total precipitation resulted from a steady increase during the 1920s to 1970s. There was substantial spatial variability in the precipitation trends which will be detailed in the following.

The trends in annual and seasonal normalized precipitation are provided in Fig. 8. Annual precipitation has increased by 5% to 30% during 1900–1998 in different areas of southern Canada. This annual positive trend is significant from coast to coast, with the exception of southern Alberta and Saskatchewan. The trend is also spatially consistent with the precipitation trend in the U.S. (Karl et al., 1996). While the significant increase in the annual total precipitation in B.C. and southeastern Canada extended to the U.S., the insignificant, positive trend in the Canadian Prairies gradually changed to a negative trend south of the Canada-U.S. border with the largest negative trend in Montana and Wyoming. Precipitation increase was greatest, in terms of percentages, in eastern Canada throughout the four seasons, although the trends are not statistically significant in southern Quebec during winter and spring. Precipitation has increased the least in the Prairies with significant trends during the winter, and in B.C. the increase in precipitation is significant in all four seasons. These findings also generally agree with the results of Groisman and Easterling (1994). Although results were based on a much less rigorous adjustment procedure

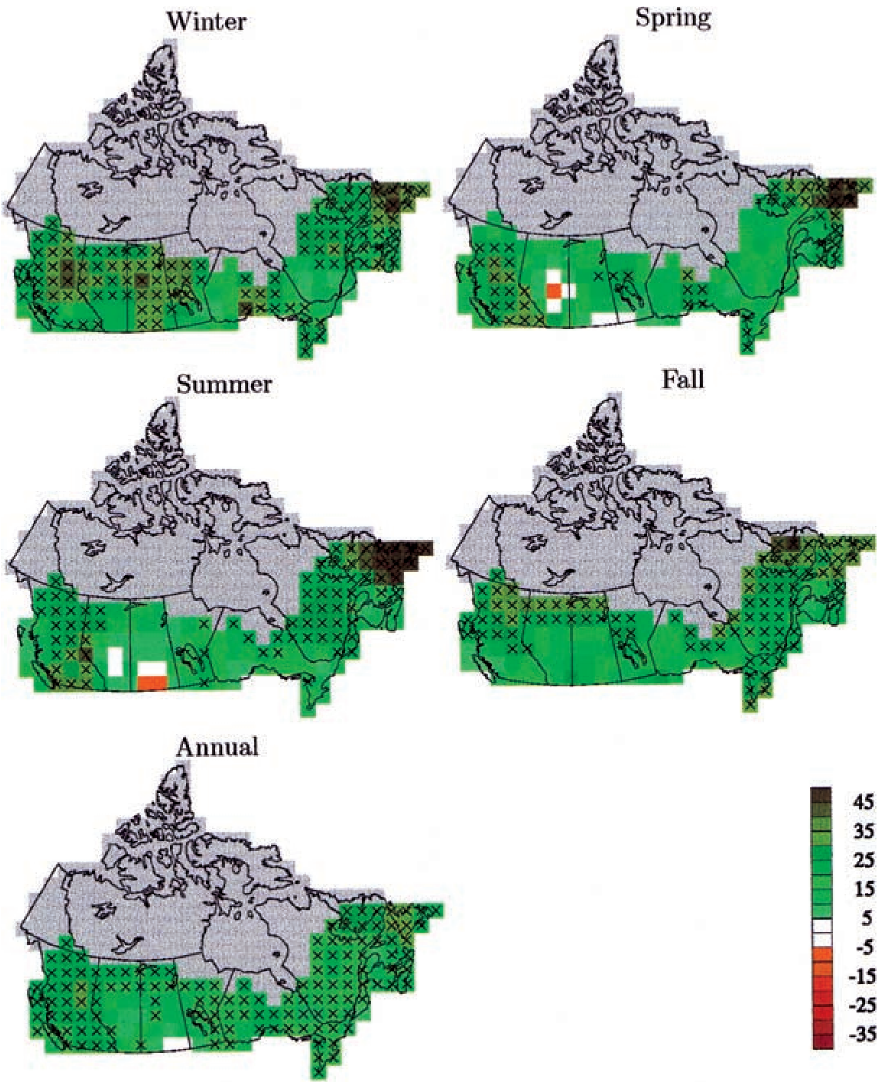

Fig. 8 Trends in precipitation totals from 1900–1998. Units are percent change over the 99-year period. Grid squares with trends statistically significant at 5% are marked by crosses. Grey areas indicate insufficient data.

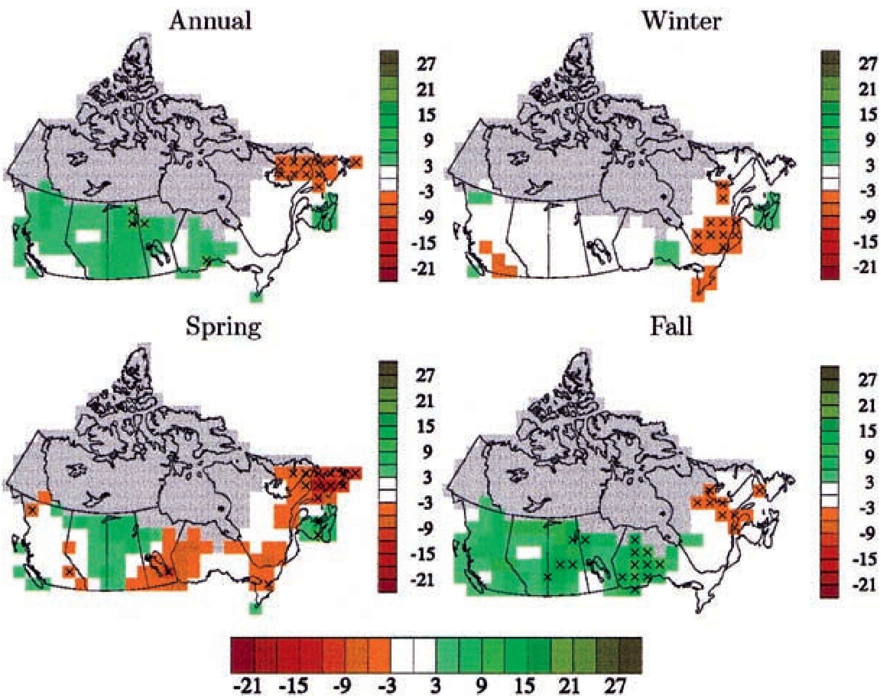

Fig. 9 As in Fig. 8, but for the ratio of snow to precipitation totals.

and a smaller dataset, these researchers showed an increase of more than 10% in the annual precipitation over the last century in southern Canada. Our investigation provided spatial distribution of the trends and indicated that the major source of this increase was due not only to changes in eastern Canada (as suggested by Groisman and Easterling), but also due to the increase in the west in B.C.

Overall, the annual ratio of snowfall to precipitation has increased during the period 1900–98 in southern Canada with a few regions with negative trends (Fig. 9). These increasing trends are due mostly to the increase in winter precipitation (Fig. 8) which generally falls as snow as well as to an increase in the ratio during autumn. Strong and significant negative trends are also observed in eastern Canada, especially in spring.

4 Trends for 1950–1998 (whole of Canada)

a *Temperatures*

The annual mean temperature anomalies relative to the 1961–1990 mean for the whole of Canada (1950–1998) are also shown in Fig. 3. No significant linear trend is detected for the entire country during the period.

The most striking feature in the pattern of the trends in maximum temperature

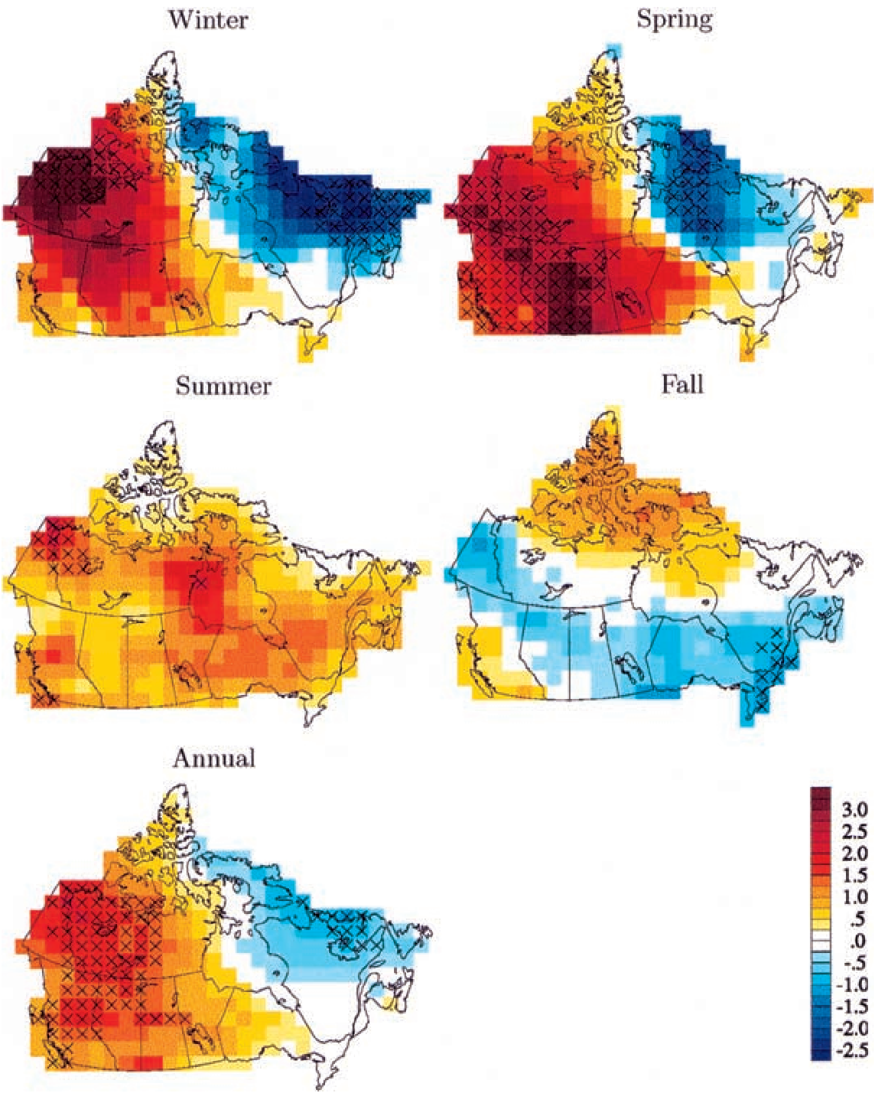

Fig. 10 Trends in daily maximum temperature from 1950–1998. Units are °C per 49-year period. Grid squares with trends statistically significant at 5% are marked by crosses.

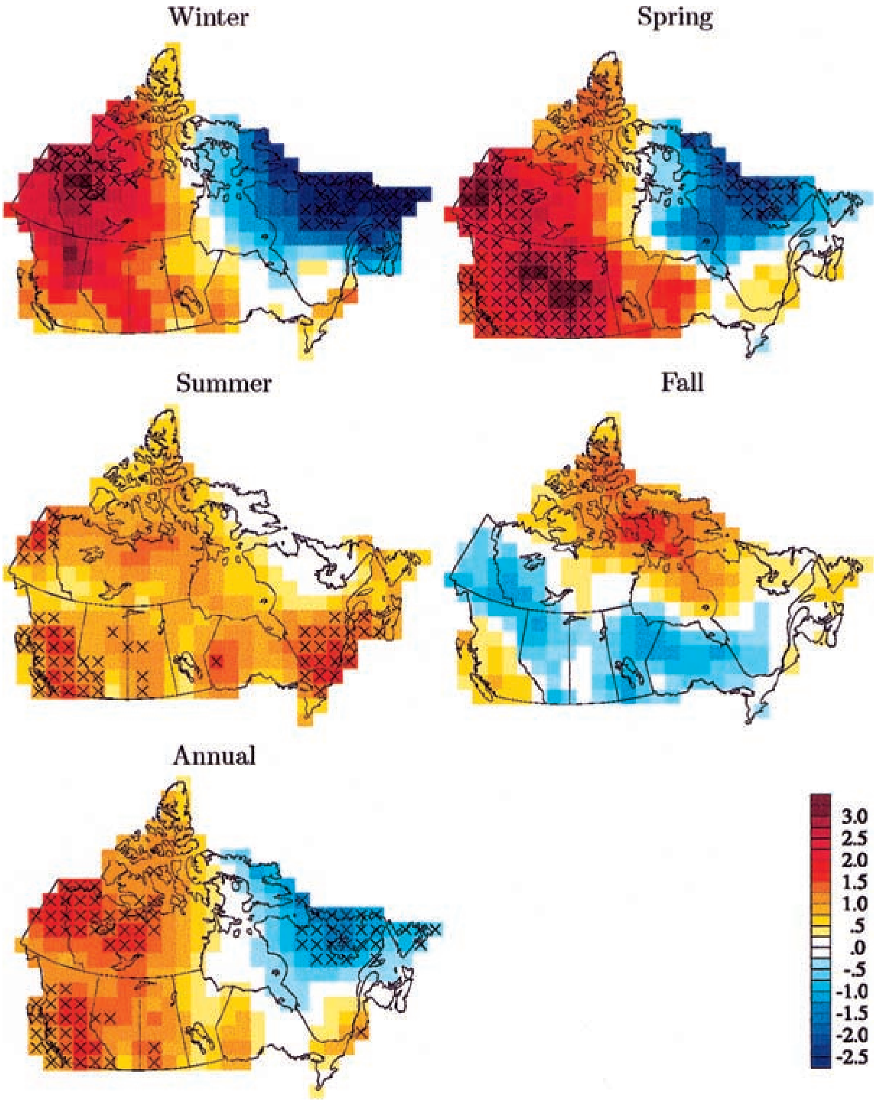

Fig. 11 As in Fig. 10, but for daily minimum temperature.

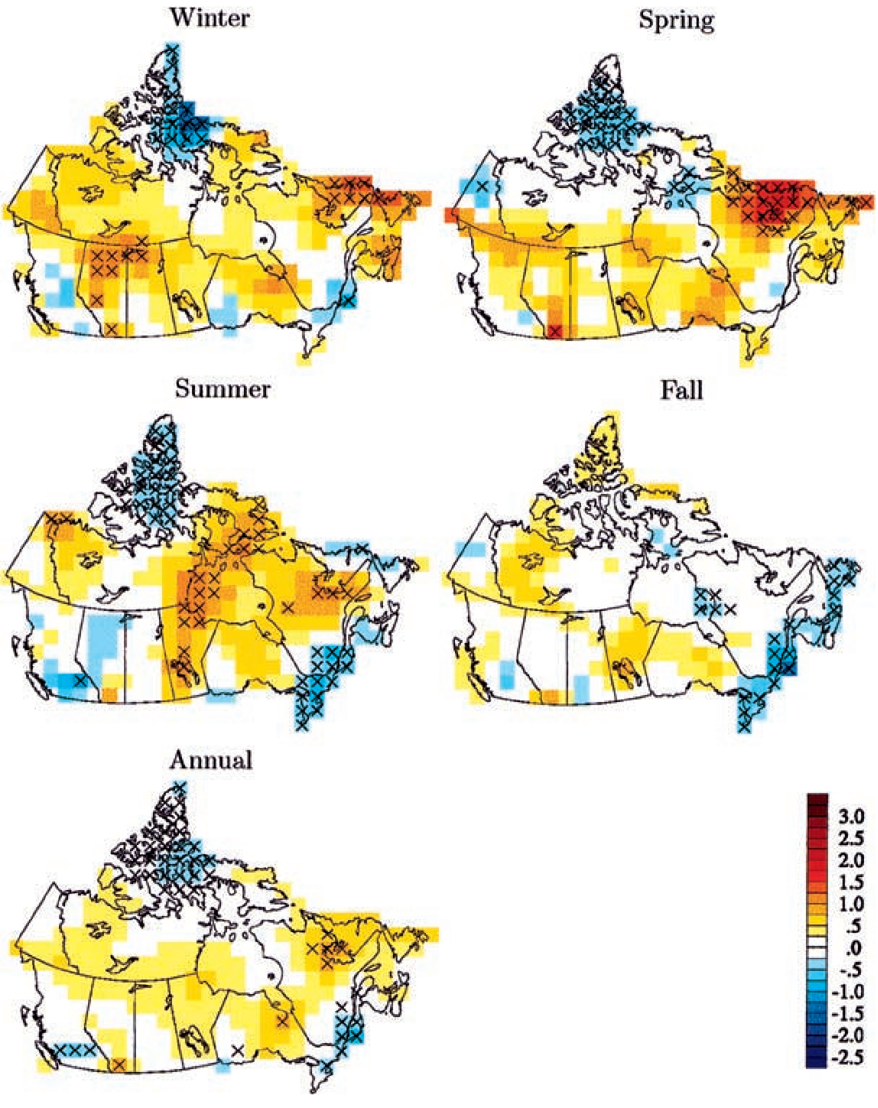

Fig. 12 As in Fig. 10, but for daily temperature range.

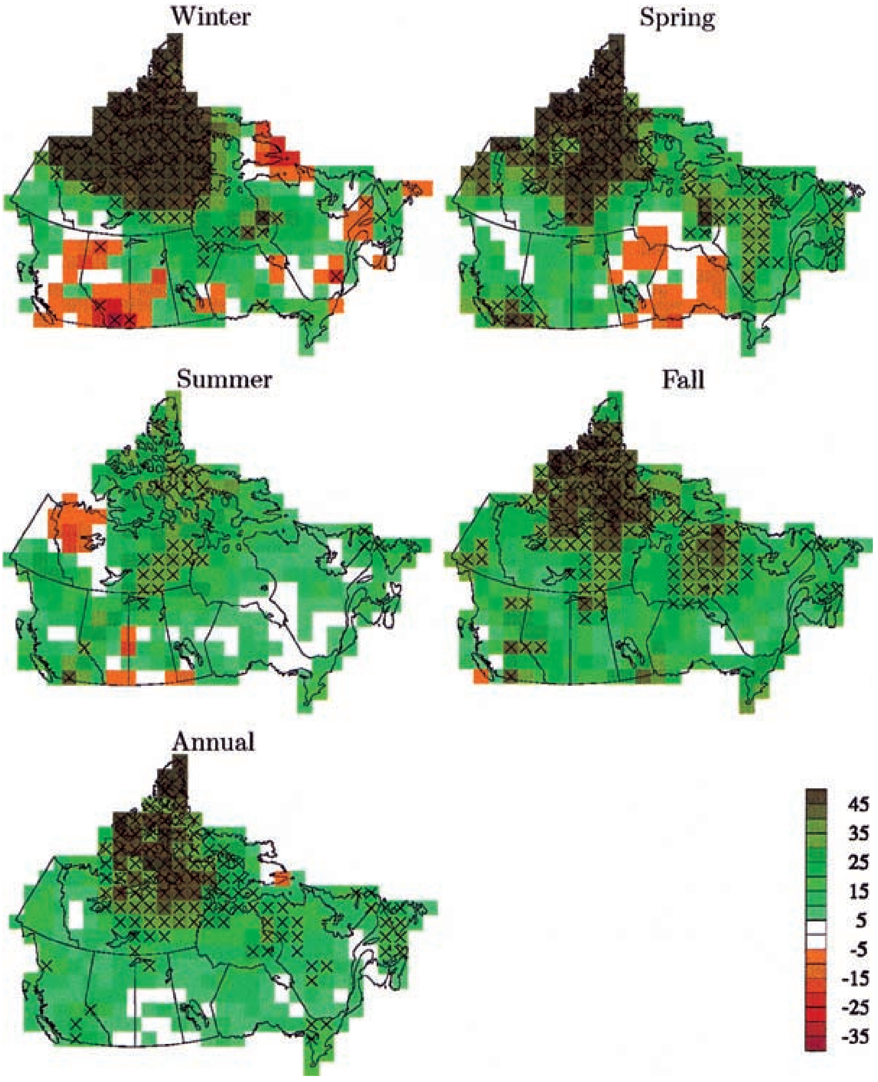

Fig. 13 Trends in precipitation totals from 1950–1998. Units are percent change over the 49-year period. Grid squares with trends statistically significant at 5% are marked by crosses.

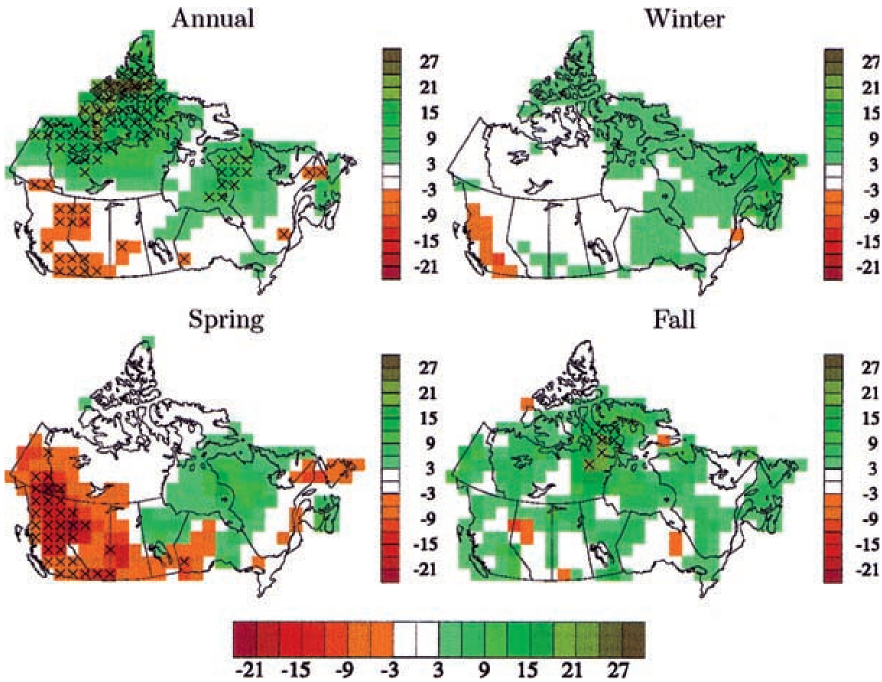

Fig. 14 As in Fig. 13, but for the ratio of snow to precipitation totals.

during this period is the contrast between the west, where strong positive trends are observed, and the northeast, where strong negative trends prevail (Fig. 10). The annual maximum temperature has significantly increased by 1.5 to 2.0°C over the 49-yr period in northern B.C. and the Mackenzie basin, and significantly decreased in the northeast part of the country with largest cooling trends of about 1.5°C over the same time period. The spatial patterns of trends are similar for winter and spring. Mean daily maximum temperatures have warmed by more than 3.0°C during the last 49 years in some regions of western Canada in both winter and spring, whereas they have cooled by more than 2°C in some northeast areas. It should be noted that the increase in winter maximum temperature is statistically significant only in some parts of the Mackenzie basin while the area with significant warming is much larger in spring. There are few significant trends during both summer and fall. Mean daily maximum temperatures have increased over most of the country during the summer. In fall, increases have occurred only in the high Arctic and B.C.; decreasing values have occurred in the rest of Canada.

Figure 11 shows the spatial distribution of the trends in annual and seasonal minimum temperatures. These have only small differences with respect to their maximum temperature counterparts. The areas with significant warming have shifted from northern Alberta to southern B.C. in the annual temperature. Contrary to findings for the 1900–1998 period during the winter and spring, the magnitude of warming is slightly less in the minimum than in the maximum temperature. The significant summer warming extends over a larger area, while the warming/cooling pattern during the fall remains almost the same as that for maximum temperatures.

The analysis of trends in mean temperature for the period 1950–1998 (not shown) displays similar results to those obtained from maximum and minimum temperatures. The annual mean temperature for Canada has increased by 0.3°C over the last 49 years, but this increasing trend was not statistically significant. It should be noted that the strong warming in winter mean temperature observed in the Mackenzie basin was generally not significant at the 5% level, due to the high variance of winter temperatures in this region.

The trends in DTR calculated for the period 1950–1998 (Fig. 12) are quite different from those obtained for 1900–1998 (Fig. 6). Areas with positive trends are much larger than those with negative trends; but the statistical significance of trends is weak. Some small regions in the high Arctic and across the southern part of the nation showed significant negative trends. Areas with significant increasing trends are located in northeast Canada in the annual, winter and spring time series and correspond to areas of regional cooling. Significant negative trends are found in the high Arctic and populous southeastern regions during the summer and fall. In general, these results agree with the findings of Karl et al. (1993a) who noted that the DTRs have not been increasing over the interval 1951–1990 in central Canada, and that the country experienced only a moderate decrease during the summer and fall.

The trend in Canadian temperature during the second half of the 20th century has a large-scale, hemispheric background, consistent with the mid-latitude Northern Hemisphere continental warming (during summer and spring) and oceanic cooling seen by Nicholls et al. (1996). It may also reflect changes over the global ocean-atmosphere circulation in the time period. In fact, cooling in northeastern Canada in the last five decades is part of a general decline in northern North Atlantic temperature (Morgan et al., 1993). Winter temperature variability in northeastern Canada at decadal and longer timescales is closely connected with variability of the North Atlantic Oscillation at the same timescales (Shabbar et al., 1997). The warming trend in western Canada is also closely matched by strong warming in sea surface temperature (SST) of the eastern Northern Pacific. This is a part of the El Niño Southern Oscillation (ENSO) like interdecadal variability of Pacific SST; i.e., warming in the tropical and eastern North Pacific and cooling over the central North Pacific (Zhang et al., 1997; Zhang et al., 1998).

Comparison of our findings for southern Canada for the periods 1900–1998 and 1950–1998 reveals a striking difference in DTR; significant negative trends for 1900–1998 in southern Canada are replaced by spatially non-coherent and generally positive trends in the same region. This discrepancy in the trends between the time periods may reflect changes in the total cloud cover. The increase of cloud amount during the first half of the century (Henderson-Sellers, 1989) probably contributed to a faster increase in minimum than in maximum temperatures. In the second half of the century, cloud amount was virtually unchanged and maximum and minimum temperatures changed at more or less the same rate. Thus no spatially consistent trend in DTR, or difference in the trends for minimum and maximum temperatures, was found during 1950–1998.

b *Precipitation*

Time series of precipitation anomalies (in percentages of 1961–1990 mean) for all of Canada are also displayed in Fig. 7. Annual precipitation increased by 5% during the 1950–1998 period. There was also substantial spatial variability in the precipitation trends.

As depicted in Fig. 13, annual precipitation totals have generally increased by 5% to 35% across the nation during 1950–1998. Significant increases occurred mostly in the Arctic (north of 60°N). Overall, precipitation totals have also shown significant increases in all seasons, and some areas of decrease mostly during the winter time. As noted by Mekis and Hogg (1999), these increases in precipitation are not likely caused by the introduction of the Nipher gauge, the most likely source of artificial increase in the mid-1970s, since most of the changes occurred prior to its introduction.

The trends in the ratio of snow to total precipitation essentially reflect the combined effects of both precipitation and temperature (Fig. 14). In the annual series, the trends are negative in the south and significantly positive in the north, which fits well with findings for southern Canada by Karl et al. (1993b). The decreasing trend in the annual ratio for southern Canada has resulted primarily from the decrease in winter precipitation, which usually falls as snow (Fig. 13), and from the decrease in spring snowfall. As well, snowfall amounts have decreased in both winter and spring. Brown and Goodison (1996) reported similar trends in the depth of snow on ground measurements. For winter, there is not much change found in the ratio. It is assumed that the increase of spring temperature is so high that it effectively decreased (increased) the proportion of snow (rain) in the total precipitation for the season, although total precipitation was essentially unchanged (see Fig. 13). Such linkage between spring temperature and precipitation was also reported by Brown and Goodison (1996) and Brown and Braaten (1998).

Winter precipitation during 1900–1998 has increased in southern Canada while it has decreased over large areas during 1950–1998. As well, there are more areas with a decreasing ratio of snow to total precipitation during the spring for the period 1950–1998 than for the period 1900–1998. This emphasizes the need to study decadal and multi-decadal variability of different climate variables in order to gain a better understanding of climate trends and variability.

Trends identified in Canadian precipitation are most likely a regional manifestation of the general tendency of precipitation to increase for high and mid-latitude continents of the Northern Hemisphere in the 20th century. Similar trends were identified in Russia. Wang and Cho (1997) showed upward trends in Russian precip-

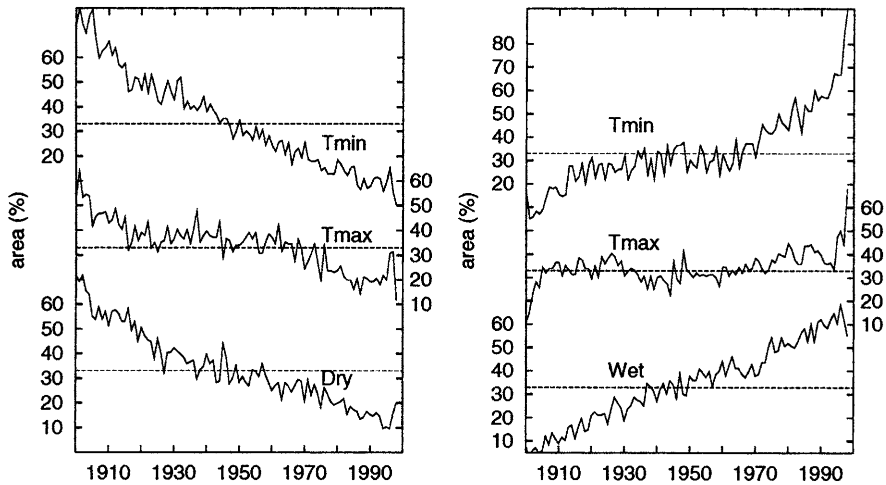

Fig. 15 Percentages of southern Canada affected by abnormally dry, cold conditions (left panel) and wet, warm conditions (right panel). Tmin and Tmax correspond to minimum and maximum temperatures, respectively.

itation (50°N to 70°N) during 1881–1989. Ye et al. (1998) reported increases in winter snow depth over most of northern Russia, but decreases over most of southern Russia during 1936–1983.

5 Indices of abnormal and extreme climate

a *1900 to 1998*

Annual time series of indices of abnormal climate for southern regions for the period 1900–98, are consistent with the results of the above trend analysis and are displayed in Fig. 15. Areas affected by abnormally dry conditions (precipitation is less than the 34th percentile) have been gradually decreasing. At the same time, areas affected by abnormally wet conditions (precipitation is more than the 66th percentile) increased. These trends agree with an overall increase in annual precipitation. The areas affected by abnormally low maximum temperatures (temperature is less than the 34th percentile) have decreased, particularly since the 1960s. Areas experiencing abnormally high maximum temperatures, however, showed little trend. The portion of southern Canada experiencing abnormally low minimum temperature was drastically decreased. The reverse was the case for the minimum temperature in its higher quantile. More areas with temperatures in the higher quantile and fewer areas affected by lower quantile temperature vividly displayed the warming picture in southern Canada. Like other parts of the world, Canada has not become hotter (no increase in higher quantiles of maximum temperature), but has become less cold. Because of gradual changes in these areal indices over time, it appears that

TABLE 1. Changes in the area of southern Canada affected by abnormal climate conditions computed as the differences between the 1950–1998 mean and the 1900–1949 means. Units are percent.

	Precipitation		Max. Temperature		Min. Temperature	
	Dry	Wet	Cold	Warm	Cold	Warm
Annual	–23.4	27.3	–12.8	5.2	–32.2	20.1
Winter	–25.6	21.4	–10.8	7.1	–15.7	9.8
Spring	–12.1	12.3	–10.2	11.8	–21.1	20.3
Summer	–13.9	14.3	–8.5	6.7	–30.6	30.3
Fall	–14.4	17.3	–5.9	–5.1	–20.5	11.6

the warming trend, especially that, in minimum temperature, is not likely caused by sudden step jumps in the data.

On seasonal timescales, the time variations of the areal extent of southern Canada affected by abnormal climate conditions also agreed well with the results of trend analysis. Overall, there was a decrease (an increase) in the areas affected by dry (wet) conditions for all seasons, but the amplitudes of the changes differ from one season to the other. Areas, affected by cold (warm) conditions also decreased (increased). The extent of decrease in the area affected by colder, and of increase by warmer, maximum temperature are about half of their counterparts in the minimum temperature.

Areas affected by abnormal climate conditions were quite different between 1950–1998 and 1900–1949. Table 1 displays the changes in indices of abnormal climate computed as differences between the 1950–1998 mean and the 1900–1949 mean. In winter, areas affected by dry conditions were reduced by 25.6% and those affected by wet conditions were increased by 21.4% from the first half to the second half of the century. The largest reduction in the area experiencing colder climate appeared in minimum temperature in summer. Accompanying this reduction is a sharp increase (30.3%) in the areas affected by warm conditions. Since the long-term averaged values of the abnormal climate indices must be 33.3%, such an increase in the index indicates that 90% of abnormally warm daily minimum temperatures in summer occurred in the second half of the century.

Changes in the area affected by extreme climate conditions (precipitation or temperature below the 10th or above the 90th percentiles of their relevant time series) between the two halves of the century generally follow the changes in the abnormal climate conditions; but there are differences, especially in summer for precipitation (Table 2). More specifically, areas affected by both extreme dry and extreme wet conditions during summer increased. That is, while it was generally wetter in the second half of the century, areas affected by extreme dry conditions actually increased (17% of century-long average) in summer. The fact that summer temperature increased, and that areas affected by both extreme dry and extreme wet conditions increased as well during the season, may be an indication of an enhanced hydrological cycle. This is consistent with GCM simulations that hydrological

TABLE 2. Changes in the area of southern Canada affected by extreme climate conditions computed as the differences between the 1950–1998 mean and 1900–1949 means. Units are percent.

	Precipitation		Max. Temperature		Min. Temperature	
	Dry	Wet	Cold	Warm	Cold	Warm
Annual	–3.6	10.1	–3.1	8.3	–11.4	11.5
Winter	–7.3	5.1	–1.1	5.0	–3.0	4.6
Spring	–0.0	5.1	–3.5	6.4	–7.5	8.5
Summer	1.4	5.2	–7.4	9.0	–10.7	16.4
Fall	–5.5	7.8	0.4	–1.3	–6.2	4.8

cycles will be enhanced in a warmer world caused by the increase of greenhouse gases in the atmosphere (Kattenberg et al., 1996). All three indices which represent areas of Canada affected by extreme dry conditions during summer, by extreme warm temperatures, and by extreme wet conditions during cool seasons have increased. Karl et al. (1996) also showed an increase in the GCRI which uses those three (with two other) indicators for the U.S. It appears that the changes in the extreme climate indices for Canada and the GCRI for the U.S. point in the same direction: a possible response of regional climate in North America to the increase of greenhouse gases in the atmosphere. More studies are needed before we can conclude that such changes are the manifestations of anthropogenic climate change.

Precipitation and temperature are the two most important climate variables affecting society. Coincident changes in both variables, such as abnormally dry when warm, may have more severe impacts on society than changes to only one variable. It is both interesting and important to examine the areas affected by joint abnormal conditions (defined as below 34th or above 66th percentiles of their relevant time series) of these two variables; i.e., areas affected by four different combinations of wet/dry and warm/cold conditions. Figure 16 presents the time series of areas affected by abnormal values of both precipitation and mean temperature (average of maximum and minimum temperature) combined. Areas affected by combined low precipitation and low temperature decreased dramatically throughout the 20th century in annual and seasonal time series. The area of southern Canada experiencing wet and warm conditions was, meanwhile, getting larger. This is a clear reflection of the fact that both temperature and precipitation in the region have generally been increasing. Changes in the areas affected by abnormally dry and warm conditions, and by abnormally wet and cold conditions between the two halves of the century, are much smaller and show some seasonal variability. The seasonal distribution of trends in abnormally dry and warm conditions, which can be considered to be a proxy of drought, are very interesting. The fall and winter time series of areas affected by abnormally dry and warm conditions have systematically decreased during the century, but in a separate study we found that the same index for the growing seasons, spring and summer, has respectively increased and remained constant over the same period.

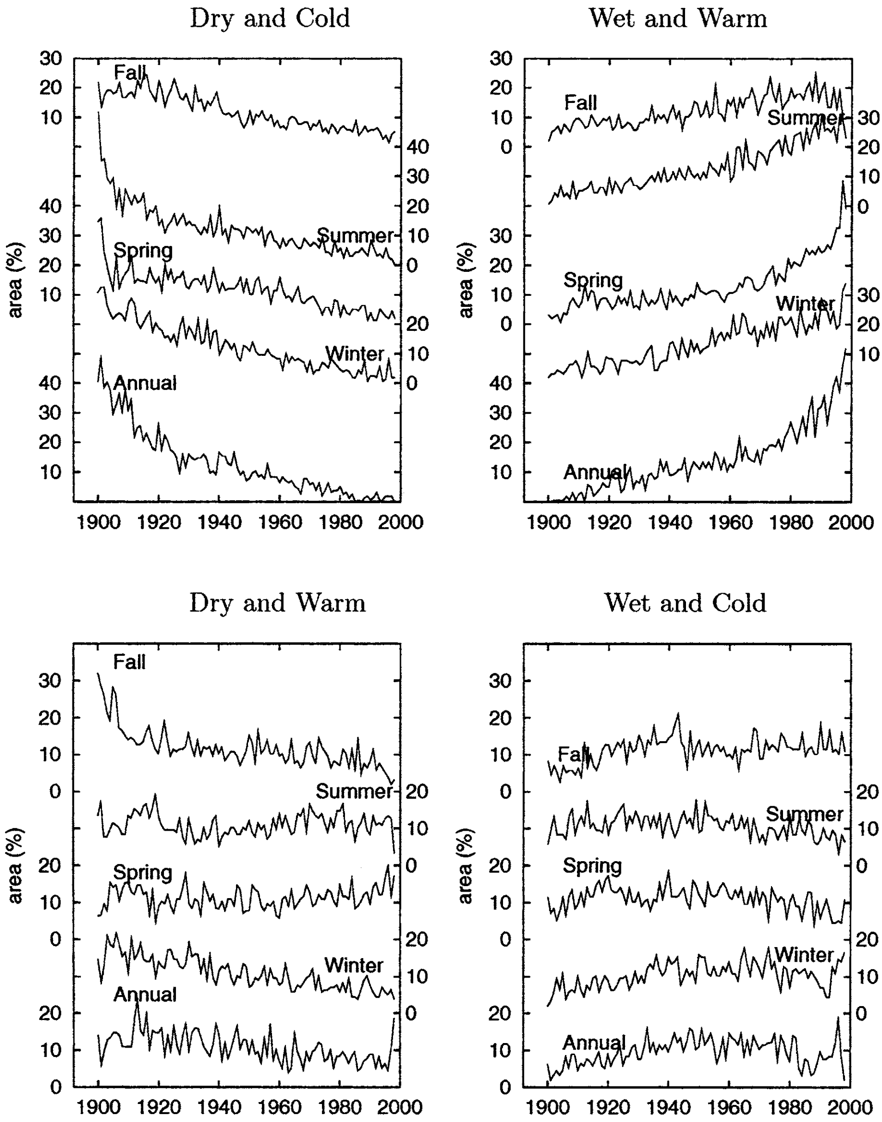

Fig. 16 Percentages of southern Canada covered by abnormal conditions.

b *1950 to 1998*

The areas of Canada as a whole affected by abnormally dry conditions gradually decreased in the last five decades of the century, whereas areas affected by abnormally wet conditions increased decade by decade (not shown). Because it has warmed in the west and cooled in the northeast during this period, no consistent trends were found in the abnormal temperature indices (not shown). It is worth noting that the last two decades show more areas affected by abnormally high temperature (in both maximum and minimum temperatures). Indices of extreme climate for the past five decades displayed similar patterns to those for indices of abnormal climate. Areas affected by combined dry and cold conditions decreased with an increase in areas affected by wet and warm conditions throughout the period. However, these may reflect dominance of these indices by precipitation trends because areas affected by dry and warm conditions also decreased.

6 Conclusions and discussion

Statistical optimal interpolation was employed to generate a high quality Canadian monthly gridded dataset of temperature and precipitation anomalies for the 20th century with the best available station time series as input. Using the gridded dataset, spatial distribution of trends obtained from annual and seasonal time series of six climate variables, maximum, minimum and mean temperatures, diurnal temperature ranges, precipitation totals and ratio of snowfall over total precipitation, have been presented for southern Canada (south of 60°N) for the period 1900–1998, and for the whole country for the period 1950–1998. The statistical significance of the trends has also been assessed.

Annual mean temperature has warmed an average of 0.9°C in southern Canada over the last century. Associated with this increase in mean temperature is a relatively smaller increase in daily maximum temperature and a larger increase in daily minimum temperature. In this century, the increases have resulted in a decrease in diurnal temperature range by 0.5 to 2.0°C. The bulk of decline in DTR occurred during the first half of the century, coinciding with an increase in cloud cover during that period. Both of these results are broadly consistent with greenhouse gas induced climate change, but the timing of the changes, coming prior to the most significant increase in greenhouse gases, suggests that other mechanisms may be responsible. Examining the areas affected by abnormal and extreme temperature confirmed the above analysis. It also suggested that the probability distribution of minimum temperature has shifted with a higher mean but only the left-hand side of maximum temperature distribution has been shifted upward. This indicates that southern Canada has not become hotter but less cold.

Total precipitation has also increased over the last 99 years by 12% in southern Canada. It should be mentioned that the increases in annual precipitation totals do not directly relate to the period of increased cloud cover. Precipitation has a steady increasing trend from the 1920s to 1970, while the major increase in cloud cover occurred during 1936–1950 in mid-latitude Canada (Henderson-Sellers, 1989). The precipitation trend appears to have stopped in about 1970 for the annual time series but not for seasonal time series. There were increasing trends in winter and autumn, decreasing trends in spring and no trend in summer (not shown).

The ratio of solid to total precipitation has also increased; but the trend is not significant. Decreasing trends were observed mostly in southeast Canada in spring. These may be related to changes in both precipitation and temperature and will be discussed later. The time series of the areas affected by abnormal/extreme precipitation and temperature show gradual changes, suggesting the trend detected in precipitation and temperature was not caused by climate jumps.

For the period of complete data coverage, 1950–1998, Canada as a whole has warmed by 0.3°C. There is a strong pattern of warming in the southwest and cooling in the northeast. The maximum and minimum temperatures have increased at a similar rate which has resulted in a slight overall increase in the DTR. Areas affected by abnormal temperatures did not show increasing or decreasing trends (not shown). Overall, there has been an increase of 5% to 35% in annual precipitation totals in Canada during 1950–1998. Although strongest increases were in the north, winter precipitation exhibited decreasing trends in some areas over southern Canada. The increasing trend in precipitation is reflected in the abnormal precipitation indices which showed more areas being affected by abnormally wet conditions, and fewer areas being affected by abnormally dry conditions.

The most interesting finding based on the analysis of the joint occurrence of abnormal temperature and precipitation involved the drought-like conjuncture of warm and dry conditions. In spite of the general increase in precipitation throughout the century, the area affected by abnormally warm and dry conditions in summer remained constant, and has increased in the important spring growing season.

The trend of the ratio of snowfall to total precipitation is complex. It is related to the trends in both precipitation and temperature, as well as the temperature itself. Based on 50 years of monthly snowfall water equivalent and mean temperature data, Davis et al. (1999) analysed the snowfall temperature relationship in Canada. They found that the relationship is positive in high latitudes but is negative in southern Canada, along both coasts, and east of the Rockies. The transition zone, north of which warmer months receive more snowfall than colder months, migrates southward from autumn to winter and northward from winter to spring. In southern Canada, spring temperatures have increased, greatly shortening the period of freezing temperatures suitable for snowfall and resulting in a decrease in the ratio. In addition, the decreased snowfall has also helped to enhance the spring temperature response through the snow cover feedback (Brown and Goodison, 1996; Brown and Braaten, 1998). In northern Canada, most temperature increases have occurred in seasons with below freezing temperatures. Warmer conditions have made more moisture available to precipitation events, and these have been in the form of snow so that the ratio of snowfall to total precipitation has increased. These findings are consistent with GCM simulations which have attributed snow accumulation in the arctic region to global warming (Ye and Mather, 1997). The increases in total snowfall amount have also resulted in an increase in the number of heavy snow events (Zhang et al., unpublished manuscript) in northern Canada.

The fact that many previous findings on Canadian climate trends (e.g. Skinner and Gullett, 1993; Environment Canada, 1995) are supported by our analysis of the best available adjusted data indicates that these trends are not artificial (e.g. caused by changes in location of observation sites or programs). Using the most up-to-date and comprehensive dataset confirms the trends to be reliable and robust. Comparison with trends identified in 20th century annual total precipitation and mean temperature for the U.S. (Karl et al., 1996), shows that trends computed from Canadian data for the same period and the same variables are spatially consistent across the Canada-U.S. border.

The results of trend analyses could be influenced by the time period used for the analyses. Quantitative analyses of the influence of decadal and multidecadal variations on the trends are difficult. We are investigating climate variability at both interannual and interdecadal timescales. The results will be reported in the near future. Preliminary findings indicate that spatial distribution of trends similar to those reported in this paper can still be identified after the removal of variability at interannual and interdecadal timescales.

We offered several improvements in this study. Firstly, it is based on the most reliable and recently adjusted temperature and precipitation data available. Secondly, the model used for the trend estimation takes into account the autocorrelation observed in the climate time series, thus the accuracy of estimation and statistical significance is improved. Employing Kendall's tau instead of the least squares method strengthens the computation since Kendall's tau method is less affected by outliers and the non-normality of datasets. We computed trends in annual mean temperature over southern Canada for the last century using both least squares method and our method. The difference in the resultant trends by including/excluding the year 1998, the hottest year on record, in the computations was 10% with the least squares method, but was only 1% with our method. Our method ensures that trend calculation is accurate and robust. Thirdly, rather than using area averages for a number of broad climate regions computed from station data, the station data have been gridded prior to trend analysis. The effect of various record sizes on the computation of trend is reduced. This provided an additional reduction in the local noise and enhanced the signal to noise ratio for trend detection. Finally, we took a new look at the trends by examining the areas of the region affected by abnormal/extreme climate conditions.

The causes of the different spatial and temporal trends, such as increasing atmospheric greenhouse gases or natural climate variability, cannot be addressed by a study of this nature. There is evidence, nevertheless, suggesting that a certain degree of agreement exists between observed trends in Canadian climate and those predicted by GCMs incorporating an increase in atmospheric greenhouse gases. With new developments in GCMs, and better understanding of global and regional climate, new light will be shed on the nature of trends in Canadian climate.

Acknowledgments

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