# Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes

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ABSTRACT

Trends in Canada's climate are analyzed using recently updated data to provide a comprehensive view of climate variability and long-term changes over the period of instrumental record. Trends in surface air temperature, precipitation, snow cover, and streamflow indices are examined along with the potential impact of low-frequency variability related to large-scale atmospheric and oceanic oscillations on these trends. The results show that temperature has increased significantly in most regions of Canada over the period 1948–2012, with the largest warming occurring in winter and spring. Precipitation has also increased, especially in the north. Changes in other climate and hydroclimatic variables, including a decrease in the amount of precipitation falling as snow in the south, fewer days with snow cover, an earlier start of the spring high-flow season, and an increase in April streamflow, are consistent with the observed warming and precipitation trends. For the period 1900–2012, there are sufficient temperature and precipitation data for trend analysis for southern Canada (south of 60°N) only. During this period, temperature has increased significantly across the region, precipitation has increased, and the amount of precipitation falling as snow has decreased in many areas south of 55°N. The results also show that modes of low-frequency variability modulate the spatial distribution and strength of the trends; however, they alone cannot explain the observed long-term trends in these climate variables.

## 1. Introduction

Over the past several decades, the northern regions have experienced some of the most rapid warming on Earth (Alexander et al. 2013; Houghton et al. 2001). The annual mean temperature over the high-latitude land area has increased by almost twice the rate of the global average (AMAP-SWIPA 2011; Anisimov et al. 2007; ACIA 2005). The cause of the warming amplification in the northern regions has been attributed primarily to temperature and albedo feedbacks because of complex interactions between land surface temperature, snow cover or sea ice extent, and the atmosphere (Pithan and Mauritsen 2014; Serreze and Barry 2011). Canada, with a large northern landmass, is also experiencing rapid warming with nationwide annual mean surface air temperature increasing by 1.5°C over the period 1950–2010 (Vincent et al. 2012). This warming has been accompanied by significant changes in many other climate elements, in different parts of the country, including increases in precipitation (Mekis and Vincent 2011), decreases in the duration of snow cover (Brown and Braaten 1998), and decreases in streamflow (Zhang et al. 2001). These changes in Canada's climate have widespread impacts on the environment, economic activities, and human health, especially in the north, where warming is proceeding more rapidly and where ecosystems and traditional lifestyles are particularly sensitive to warming (Warren and Lemmen 2014; Allard and Lemay 2012).

Recent changes in Canada's climate have been attributed, at least in part, to the increase in the concentration of atmospheric greenhouse gases associated with anthropogenic activities. Evidence of an anthropogenic influence was found on temperature in the southern regions of Canada (Zhang et al. 2006), in the Arctic (Najafi et al. 2015; Gillett et al. 2008), on Arctic sea ice and precipitation (Min et al. 2008a,b), and to a lesser extent on heavy precipitation events over a large part of the Northern Hemisphere land areas (Min et al. 2011).

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Barnett et al. (2008) attributed much of the observed changes during the second half of the twentieth century seen in winter surface air temperature, river flow, and snowpack in the western United States to anthropogenic forcing.

Previous studies have documented significant links between low-frequency modes of atmospheric–oceanic variability and Canadian climate. For example, positive phases of the Pacific decadal oscillation (PDO) and El Niño–Southern Oscillation (ENSO) have been associated with warm winter temperatures in western and central Canada (Shabbar and Yu 2012; Bonsal et al. 2001; Shabbar and Khandekar 1996) and a reduction of snow cover in western Canada (Brown 1998). An abrupt transition to lower snow depths in the mid-1970s was related to a shift in the Pacific–North America (PNA) index (Brown and Braaten 1998). Interannual variations in Canadian Prairies precipitation have been associated with ENSO variations (Bonsal and Lawford 1999; Shabbar et al. 1997). Positive phases of the PNA pattern and PDO corresponded to shorter durations of ice cover on lakes and rivers (Bonsal et al. 2006), increasing streamflow regime in spring (Brabets and Walvoord 2009), and earlier high-flow season (Stewart et al. 2005). Trends toward positive modes of the North Atlantic Oscillation (NAO) were associated with cold and dry winters in northeastern Canada (Bonsal et al. 2001). Brown (2010) documented evidence of an abrupt decrease in snow depth in southern Quebec around 1980 linked to a reduction in the number of winter storms over the region (Wang et al. 2006) coinciding with a transition to more positive values of the NAO.

It is important to improve our understanding of the various mechanisms responsible for changes in regional surface climate. Large-scale oscillations have a significant influence on climate trends: at times, they can mask or enhance the trends depending on the phase of the oscillation and the time period selected for trend analysis. Canada's climate shows multidecadal-scale variability over the past century associated with oceanic and atmospheric modes: the relationships are however regionally based and are more evident during the boreal winter. Canada's climate has also been influenced by anthropogenic warming in recent decades. It is therefore a complex task to estimate the magnitude of climate trends and their potential causes.

The first objective of this study is to provide a comprehensive analysis of the climate trends in Canada, including those for temperature, precipitation, snowcover, and streamflow indices using recently updated data, and to highlight the consistency among the trends in related climate variables over similar periods of time. The second objective is to evaluate the climate trends after removing the potential effects of low-frequency variability modes in order to determine if the trends remain significant and if they become more consistent across the country. To this end, climate trends are reassessed when indices of large-scale oscillations are used as explanatory variables in the trend estimation. Section 2 describes the datasets and section 3 presents the methodology. The trends in Canada's climate are described in section 4. The climate trends after removing the influence of low-frequency variability modes are provided in section 5. A summary and discussion follow in section 6.

## 2. Data

A number of data-related issues arise when attempting to analyze climate trends in Canada. There have been changes in instrumentation, observing practices, and relocation of observing sites that have introduced nonclimatic variations in climate datasets (also called ''inhomogeneities''), which can interfere with the proper assessment of any climate trends. In addition, the climate observing surface network in Canada has changed considerably in the past, especially since the 1990s, because of the downsizing of the traditional observing network and the increased use of automated systems (Milewska and Hogg 2002). Extensive research has been carried out over the past 15 yr to develop adjusted and homogenized surface air temperature, precipitation, wind speed, and pressure data for Canada to address many of the above concerns (Vincent et al. 2012; Mekis and Vincent 2011; Wan et al. 2010, 2007). However, more work is still needed, especially to address the issues related to the introduction of automated systems for precipitation.

### a. Surface air temperature

Homogenized daily maximum and minimum temperatures for 338 locations across the country were retrieved from the second generation of homogenized temperature dataset (Vincent et al. 2012). Observations at collocated sites were sometimes joined in order to create longer time series for use in trend analysis. Daily temperatures from automatic systems were included at some stations. Two types of adjustments were performed to produce homogenized datasets. Daily minimum temperature recorded at 120 synoptic stations (mainly airports) was first adjusted to account for the bias due to the change in observing time in July 1961 (Vincent et al. 2009). A second adjustment based on the quantile-matching algorithm, as applied in Wang et al. (2014), was performed as part of the homogeneity assessment carried out by Vincent et al. (2012) to address shifts due to site relocation and changes in observing practices. The daily mean temperature is derived from the daily maximum and minimum. Monthly mean temperature is computed as the average of the daily means and is set to missing if more than five random or three consecutive daily values are missing. Seasonal and annual means are obtained if all corresponding monthly values are nonmissing. The seasons are defined as winter (December–February), spring (March–May), summer (June–August), and autumn (September–November).

### b. *Precipitation*

Adjusted daily rainfall and snowfall amounts at 464 locations were taken from the second generation adjusted precipitation dataset (Mekis and Vincent 2011). The data were adjusted to account for known measurements issues such as wind undercatch, evaporation and wetting losses for each type of rain gauge (Devine and Mekis 2008), conversion to snow water equivalent from snow ruler measurements (Mekis and Brown 2010), trace observations, and accumulated amounts from several days. As for temperature, observations from nearby collocated stations were sometimes merged to produce longer time series (Vincent and Mekis 2009). Measurements from automatic systems were not included. The adjusted daily total precipitation is the sum of the adjusted rainfall and adjusted snow water equivalent. The monthly total precipitation is the sum of the adjusted daily total precipitation amounts following the previously defined rule for missing daily temperature. Seasonal and annual totals are obtained if all corresponding monthly values are nonmissing. Trends in the ratio of snowfall to total precipitation (hereinafter "snowfall ratio") are also examined since they provide information regarding changes in solid precipitation, which is a very important climate characteristic in Canada. The snowfall ratio is defined as the total snowfall water equivalent divided by the total precipitation obtained for each season and annually and is expressed as a percentage.

### c. *Gridding temperature and precipitation data*

Since stations recording temperature and precipitation observations are irregularly distributed across the country with more stations in the south than in the north, temperature and precipitation data were interpolated to evenly spaced point locations for a better spatial representation of the climate variations over the country. Seasonal and annual temperature anomalies from the 1961–90 reference period were first obtained at individual stations. They were interpolated to 50-km spaced grid points (E. Milewska and R. D. Whitewood 2011, unpublished manuscript) using the method of Gandin's optimal interpolation (Gandin 1965; Bretherton et al. 1976; Alaka and Elvander 1972). Normalized seasonal and annual precipitation anomalies (normalized by dividing the anomalies by the 1961–90 averages) and snowfall ratio were gridded using the same method. Seasonal and annual grid point values were averaged together in order to produce seasonal and annual time series representing the whole country. The spatial representativeness of the climate network in Canada and the uncertainty associated to the interpolation were assessed in previous studies (Milewska and Hogg 2001; Zhang et al. 2000).

### d. *Snow cover*

Snow cover data were derived from daily snow depth observations made at climate and synoptic stations since the beginning of the 1950s. Most of the observations were made at open sites or near populated regions and may not be representative of the surrounding area, particularly in regions with higher terrain and forest cover. Nonetheless, these observations still represent a consistent measure of temporal and spatial variations in snow cover in Canada. The data were taken from an update of the Canadian snow cover data (Meteorological Service of Canada 2000), which includes data rescue of previously undigitized Canadian snow depth data and the reconstruction of missing values as outlined in Brown and Braaten (1998). These data were supplemented with daily snow depth observations from the Digital Climate Archive of Environment Canada to the end of the 2012/13 snow season. A homogeneity assessment of the observations was carried out by Brown and Braaten (1998) with little evidence of detectable inhomogeneities due to station relocations.

The snow cover variables selected for this analysis are the annual maximum snow depth; date of the annual maximum snow depth; and snow-cover duration (SCD), which is defined as the number of days with at least 2 cm of snow on the ground during the snow year (August–July). The SCD is also computed over the first (August–January) and second (February–July) halves of the snow year providing a more objective way to monitor snow-cover onset and disappearance than the beginning and ending dates of continuous snow cover (which are sensitive to the definition of "continuous" snow cover). The number of stations recording snow depth has seriously decreased since the mid-1990s. There are only 104 stations with sufficient data for trend analysis for 1950–2012 (allowing for 10 missing years). Snow cover data were not gridded since there are too few stations to adequately represent spatial variations over the entire country.

### e. *Streamflow*

Streamflow data were retrieved from the Reference Hydrometric Basin Network of Environment Canada

(Zhang et al. 2001; Scott et al. 1999), which has been updated to 2012 and contains daily mean streamflow observations at 226 basins, mainly located in the south, with at least 20 yr of data. The streamflow variables selected for this analysis are annual maximum and minimum daily mean streamflow (annual highest and lowest daily mean river discharge; expressed in $m^3 s^{-1}$); annual, April, and September mean streamflow; starting date of spring freshet; and river ice freezeup and breakup dates. The starting date of the spring freshet (also called high-flow season) is the date when the cumulative sum of the difference between the daily mean streamflow and its climatology reaches a minimum during the hydrological year, from October to September (Liebmann et al. 2007). In this study, there are only 53 sites with streamflow data and 20 sites with river ice breakup and freezeup dates with sufficient data for trend analysis over 1950–2012. Because of the limited number of sites with river ice data in the past 53 yr, the trends in streamflow indices are also examined over the shorter 1967–2012 period at 57 sites.

### *f. Large-scale atmospheric and oceanic oscillation indices*

Low-frequency modes of climate variability linked to the Pacific and Atlantic Oceans are investigated to assess their influence on long-term climate variations in Canada. Four main modes of variability are assessed: the North Pacific index (NPI), Pacific decadal oscillation, North Atlantic Oscillation, the Atlantic multidecadal oscillation (AMO). NPI represents Pacific Ocean–related atmospheric oscillations and is defined as the area-weighted sea level pressure over the region 30°–65°N and 160°E–140°W (Trenberth and Hurrell 1994); this index was further normalized for this study. PDO represents Pacific Ocean oscillations and is defined as standardized values of the leading principal component of the monthly sea surface temperature anomalies north of 20°N (Zhang et al. 1997; Mantua et al. 1997). In the Atlantic, atmospheric oscillations are provided by NAO that are based on the difference in normalized sea level pressure between the Azores and Iceland (Osborn 2011; Jones et al. 1997; Hurrell 1995). Atlantic oceanic oscillations are represented by AMO defined by the normalized and detrended Kaplan sea surface temperature in the North Atlantic Ocean over 0°–70°N (Enfield et al. 2001). Monthly data for atmospheric and ocean oscillations were extracted from various publically available sources. ENSO is not used in this study since its high-frequency oscillations are not helpful for explaining long-term trends. Seasonal means of the oscillations' indices were computed following the season's definition used for temperature and precipitation (winter average indices for NPI, NAO, PDO, and AMO are presented in Fig. 1).

## 3. Methodology

Since the climate observing network in the northern regions was established during the late 1940s, there are very few locations in the north with observations prior to 1948. For this reason, temperature and precipitation trends are examined for two periods: 1948–2012 for Canada (the entire country) and 1900–2012 for southern Canada (south of 60°N). The trends for snow-cover and streamflow indices were analyzed for 1950–2012. The trend calculation methodology follows Zhang et al. (2000) with slope estimation from Sen (1968) and statistical significance based on the nonparametric Kendall's test (Kendall 1955). This test is less sensitive to the nonnormality of the data distribution and less affected by extreme values and outliers as compared to the commonly used least squares method. Since serial correlation is often present in climatological time series, the method involves an iterative procedure that takes into account the lag-1 autocorrelation of the time series (Zhang et al. 2000). The temperature and precipitation trends are computed at each grid point and for the time series averaged over Canada and southern Canada. The trends for the snow-cover and streamflow indices are obtained at individual stations. The statistical significance of the trends is assessed at the 5% level (statistically significant trends are reported as significant trends in the text). The uncertainty related to the linear trend is quantified using the 95% confidence interval (reported in square brackets in the text).

A multivariate regression modeling approach was used to evaluate the degree to which low-frequency variability modes (represented by the large-scale oscillations) were able to explain annual and seasonal variations over the short and long periods of time. A regression model was first fitted to the data at each grid point (for temperature and precipitation) or each station (for snow-cover and streamflow indices). Two explanatory variables were used to represent the Pacific and Atlantic influence (e.g., the indices for PDO and NAO) and the dependent variable was the climate element (temperature, precipitation, snow-cover, or streamflow indices). Then the method based on the Kendall test (described above) was applied directly on the residuals at each grid point (or station) in order to estimate the trends after removing the effects of the low-frequency variability modes. Annual and seasonal grid point (or station) residuals were averaged together in order to produce a single time series of residuals representing the entire country (or southern Canada).

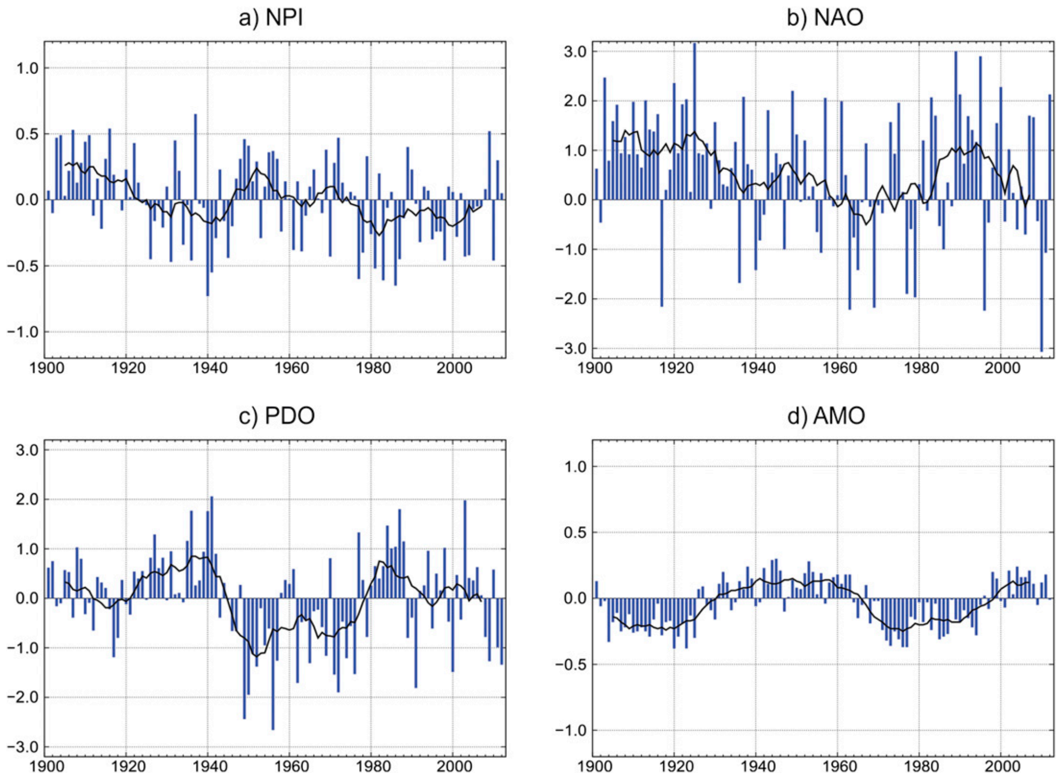


FIG. 1. Winter standardized anomalies of the (a) NPI, (b) NAO, (c) PDO, and (d) AMO indices for 1900–2012. The black line is an 11-yr running mean.

The NAO and PDO indices were first introduced in the regression model since their influence on the Canada's climate is well documented. The annual and seasonal time series of these two indices are not correlated in time and only exhibit a significant positive trend in winter PDO for 1948–2012 and a significant negative trend in winter NAO for 1900–2012. The same procedure is repeated when the NPI and NAO indices (representing atmospheric oscillations in the North Pacific and North Atlantic) and PDO and AMO indices (representing the Pacific and Atlantic oceanic oscillations) are introduced in the regression model in order to determine if the results are similar. It is important to note that the annual and seasonal time series of the PDO and NPI, or AMO and NAO, are significantly correlated in time but inversely and cannot be used in the same regression model. There was no evidence of significant trends in annual or seasonal time series of NPI and AMO over the 1948–2012 and 1900–2012 periods.

## 4. Observed climate trends in Canada

### *a. Trends in surface air temperature*

Significant trends in annual mean temperature ranging from 1° to 3°C are found almost everywhere across the nation for 1948–2012 (Fig. 2a). The anomalies averaged over the country indicate a significant increase of 1.7°C [1.1°–2.3°C] over the past 65 yr (Fig. 2b). The national time series exhibits considerable variability, although a steady increase is observed from the beginning of the 1970s to 2012. Seasonally, the greatest warming is found during winter (Fig. 3a). The winter trends are predominant in the western regions (northern British Columbia and Alberta, Yukon, Northwest Territories, and western Nunavut), ranging from 4° to 6°C over the past 65 yr. In spring, the warming is less pronounced, but significant warming trends are also dominant over the western regions (Fig. 3b). Summer mean temperature has increased much less than the winter and spring mean temperatures, but the magnitude of the warming is generally more consistent across the country (Fig. 3c). During autumn (Fig. 3d), most of the warming is observed in the Arctic and northern Quebec. Seasonal mean temperature anomalies averaged over Canada indicate significant increases of 3.3° [1.8°–4.8°C], 1.8° [0.7°–3.0°C], 1.4° [0.8°–1.8°C], and 1.5°C [0.5°–2.6°C] over 1948–2012 for winter, spring, summer, and autumn, respectively.

The results for southern Canada (Fig. 2c) show significant warming across the entire region averaging

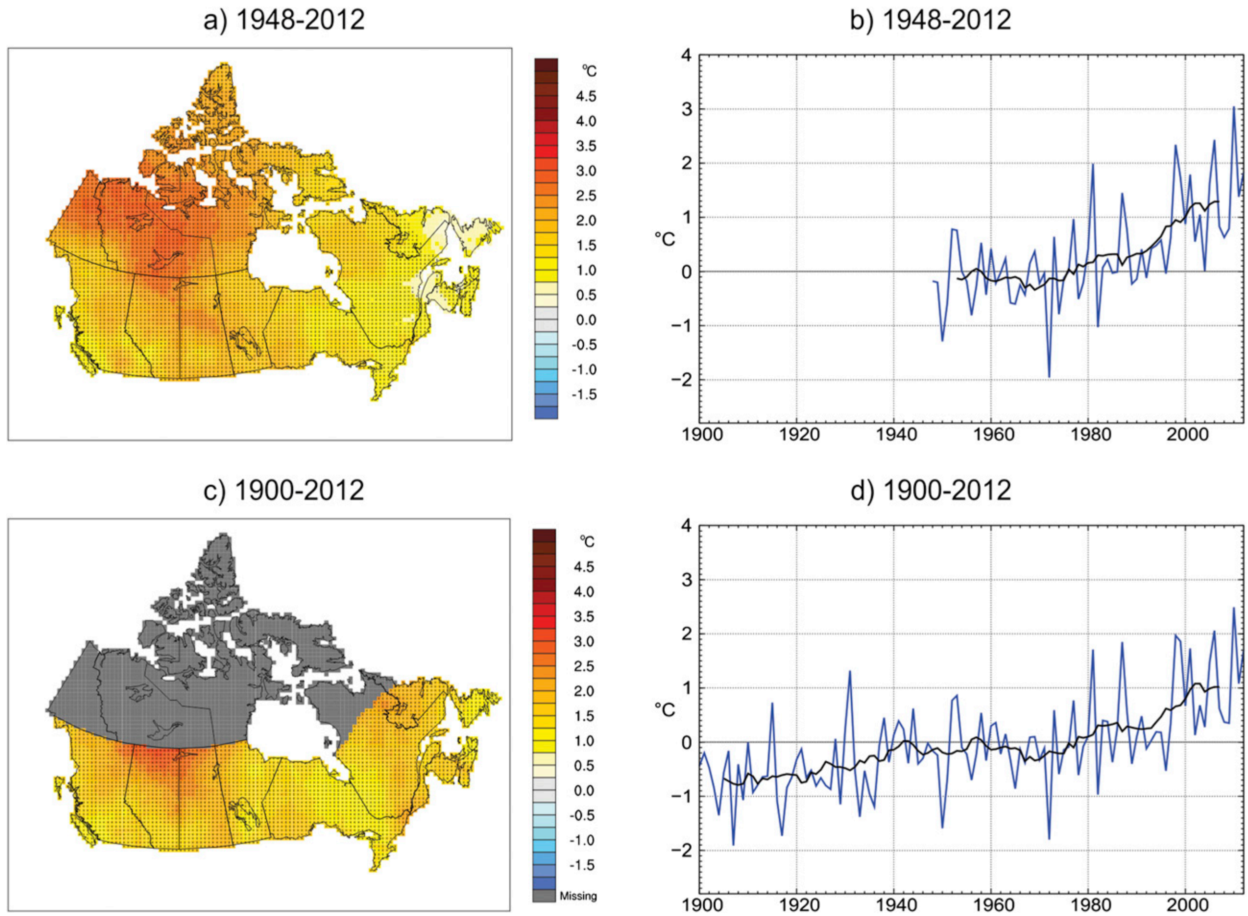


FIG. 2. Trends in annual mean temperature for (a) 1948–2012 [°C (65 yr)$^{-1}$] and (c) 1900–2012 [°C (113 yr)$^{-1}$]. Grid squares with trends statistically significant at the 5% level are marked with a dot. Annual mean temperature anomalies for (b) Canada (1948–2012) and (d) southern Canada (1900–2012). The black line is an 11-yr running mean.

1.6°C [1.2°–2.0°C] over the 1900–2012 period (Fig. 2d). The warming is not monotonic, with periods of more rapid increase evident prior to the 1940s and after the 1970s and with a modest cooling observed over 1940–70. The seasonal trend results (not shown) indicate significant warming in all seasons over southern Canada, averaging 2.6° [1.4°–3.8°C], 1.9° [1.1°–2.7°C], 1.4° [1.1°–1.8°C], and 1.0°C [0.3°–1.8°C] for winter, spring, summer, and autumn, respectively. The winter warming is more pronounced in the western regions (eastern British Columbia, Alberta, Saskatchewan, and western Manitoba), with trends of 2°–4°C over the 113-yr period. These trends are consistent with previous results (Vincent et al. 2012, 2007; Zhang et al. 2000) obtained over shorter periods of time. A reconstruction of global surface air temperature over 1901–2012 suggests that the greatest warming has occurred over northwestern North America and central Eurasia (Vose et al. 2012).

### *b. Trends in precipitation*

Annual total precipitation has increased mainly in the northern regions during 1948–2012 (Yukon, Northwest Territories, Nunavut, and northern Quebec), although some areas in the south (eastern Manitoba, western and southern Ontario, and Atlantic Canada) have also experienced significant increasing trends (Fig. 4a). There is more spatial variability in precipitation trends than in temperature trends. The anomalies averaged over the country indicate a significant increase of 19% [15%–22%] during the past 65 yr (Fig. 4b). It is important to note that the percentage anomalies in the north represent much less precipitation amounts than the same percentage in the south. In all seasons, total precipitation has increased mainly in the north (Fig. 5). In winter, decreasing trends are dominant in the southwest (British Columbia, Alberta, and Saskatchewan). There is less evidence of significant changes in the south during spring, summer, and autumn.

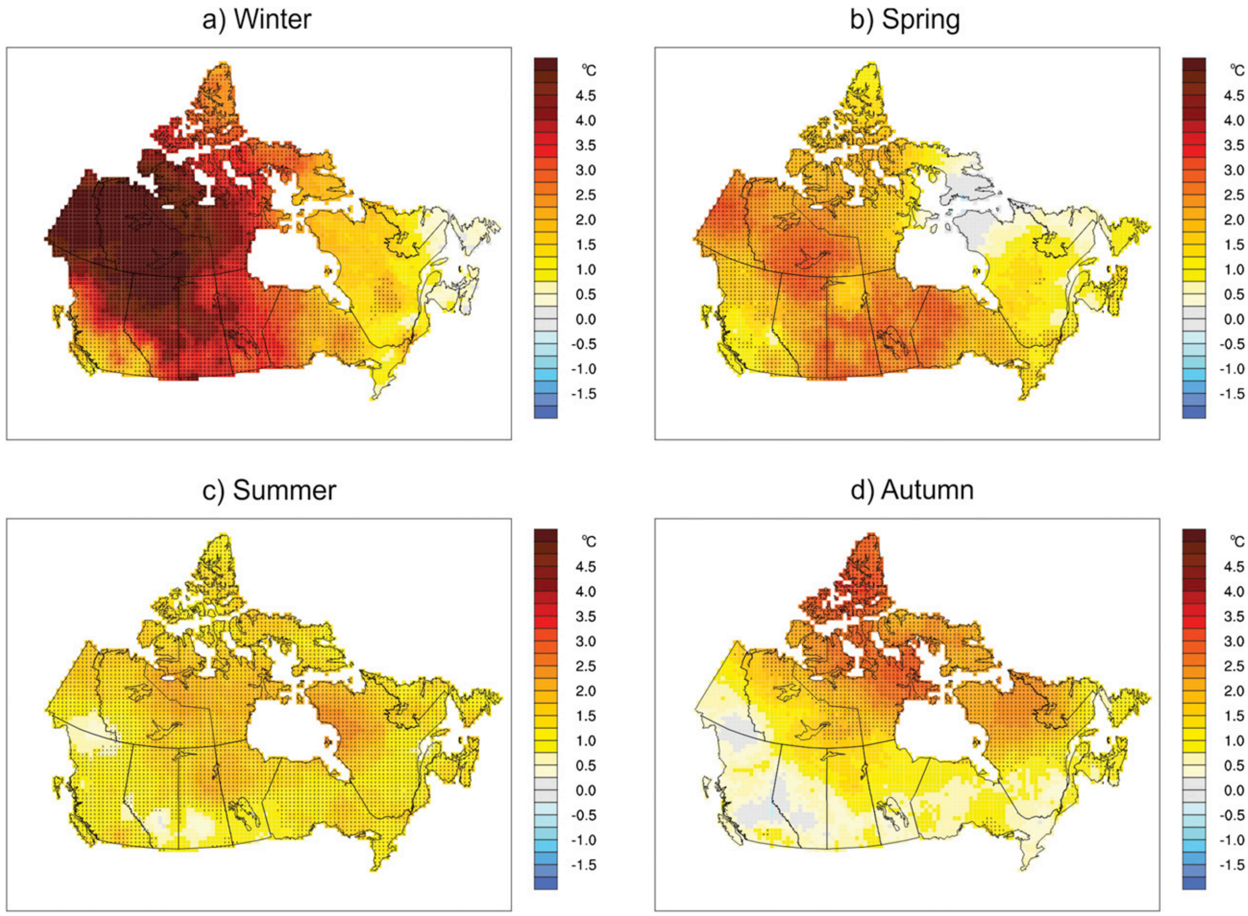


FIG. 3. Trends in mean temperature for 1948–2012 for (a) winter, (b) spring, (c) summer, and (d) autumn. Grid squares with trends statistically significant at the 5% level are marked with a dot. The units are degrees Celsius per 65 yr.

For 1900–2012, annual total precipitation has generally increased across southern Canada (Fig. 4c). The anomalies averaged over the region show a significant increase of 18% [14%–21%] during the 113-yr period (Fig. 4d). The rise in total precipitation results from a steady increase from the 1920s to the 1970s and a modest increase from the 1970s. The pattern of increasing trends is similar in all seasons (figures not presented). Seasonal positive trends are generally significant from coast to coast, with the exception of some areas in the central western (Alberta and Saskatchewan) and central eastern (eastern Ontario and southern Quebec) regions.

Trends in snowfall ratio reflect the combined effect of both precipitation and temperature. The annual trends are generally decreasing over 1948–2012 in many areas south of 65°N while they are increasing in the north (Fig. 6a). The snowfall ratio averaged over the country shows an increase from the beginning of the record to the 1970s, followed by a decrease to 2012 (Fig. 6b). The peak snowfall ratio in the 1970s is consistent with North American winter snow cover extent, which reached twentieth-century maximum values around this time (Brown 2000). In winter, there is less evidence of change although significant decreasing trends are observed in the west (British Columbia) and east (southeastern Quebec) over the past 65 yr (figure not presented). The changes are more pronounced in spring and autumn. In spring, significant decreasing trends are found across western and central Canada (Fig. 7a). Since spring precipitation has not essentially changed in the past 65 yr over this area (Fig. 5b), the decreasing trends in snowfall ratio during spring is mainly due to the spring warming (Fig. 3b), which effectively decreased the proportion of snow. A similar connection is seen in autumn, where significant decreasing trends in northern Quebec (Fig. 7b) correspond to the autumn warming over the past 65 yr (Fig. 3d).

For 1900–2012, the annual snowfall ratio has generally increased in the northern part of southern Canada

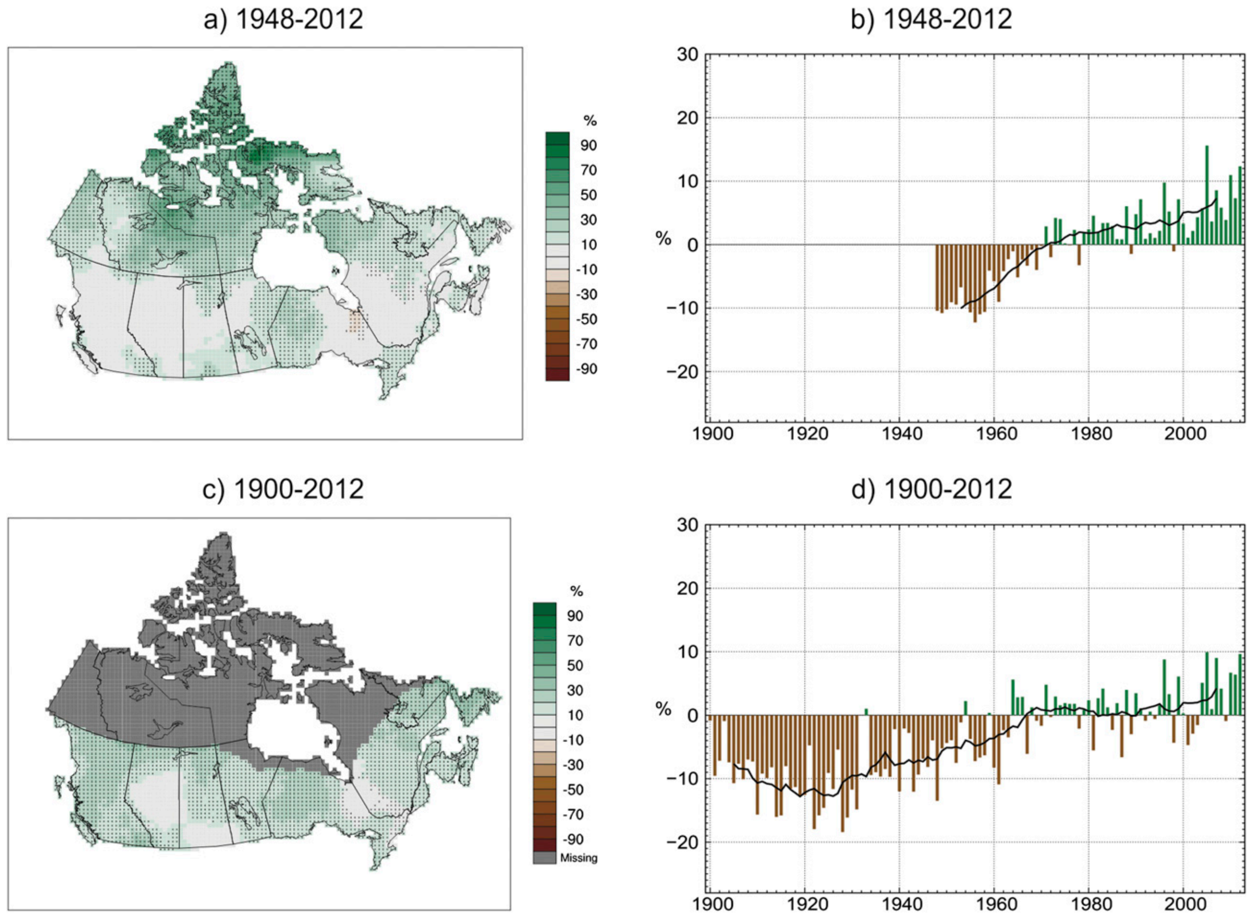


FIG. 4. Trends in annual total precipitation for (a) 1948–2012 [% $(65\,\mathrm{yr})^{-1}$] and (c) 1900–2012 [% $(113\,\mathrm{yr})^{-1}$]. Grid squares with trends statistically significant at the 5% level are marked with a dot. Annual total precipitation anomalies for (b) Canada (1948–2012) and (d) southern Canada (1900–2012). The black line is an 11-yr running mean.

(north of 55°N) and decreased in several regions in the south (Fig. 6c). The snowfall ratio averaged over the region shows a steady increase from the 1920s to the 1970s, followed by a decrease to 2012 (Fig. 6d). Similar to the shorter period, there is less evidence of change in the winter snowfall ratio (not shown), except for some small areas of decreasing trends in the west (southern British Columbia) and east (southern Quebec). The changes in snowfall ratio during 1900–2012 are more pronounced in spring and autumn when increasing (decreasing) trends are found in the northern (southern) part of southern Canada. The increasing snowfall ratio trends north of 55°N are mainly due to increasing precipitation, whereas the decreasing trends in the south are largely due to the warming trends during the past 113 yr. Precipitation trends for 1948–2012 and 1900–2012 are generally in agreement with previous findings (Mekis and Vincent 2011; Zhang et al. 2000).

### c. *Trends in snow cover*

Snow-cover duration has decreased in Canada and most of the decreasing trends are observed in spring. About 22% of the stations have significant decreasing trends in the first half of the snow year (Fig. 8a), whereas 43% of the stations have significant decreasing trends in the second half of the snow year (Fig. 8b). The SCD anomalies from the 1961–90 reference period averaged over the 104 stations show a significant decrease of 8 [3–14 days] and 10 days [5–15 days] during 1950–2012 for the first and second halves of the snow year. The trend toward earlier snow disappearance in the spring was previously documented by Brown and Braaten (1998) and is part of a hemispheric-wide trend of earlier melt of snow and ice (Lemke et al. 2007; Vaughan et al. 2013). Snow cover in North America was characterized by rapid decreases in the 1980s and early 1990s with a significant decreasing trend in April snow water equivalent for 1915–97 (Brown 2000).

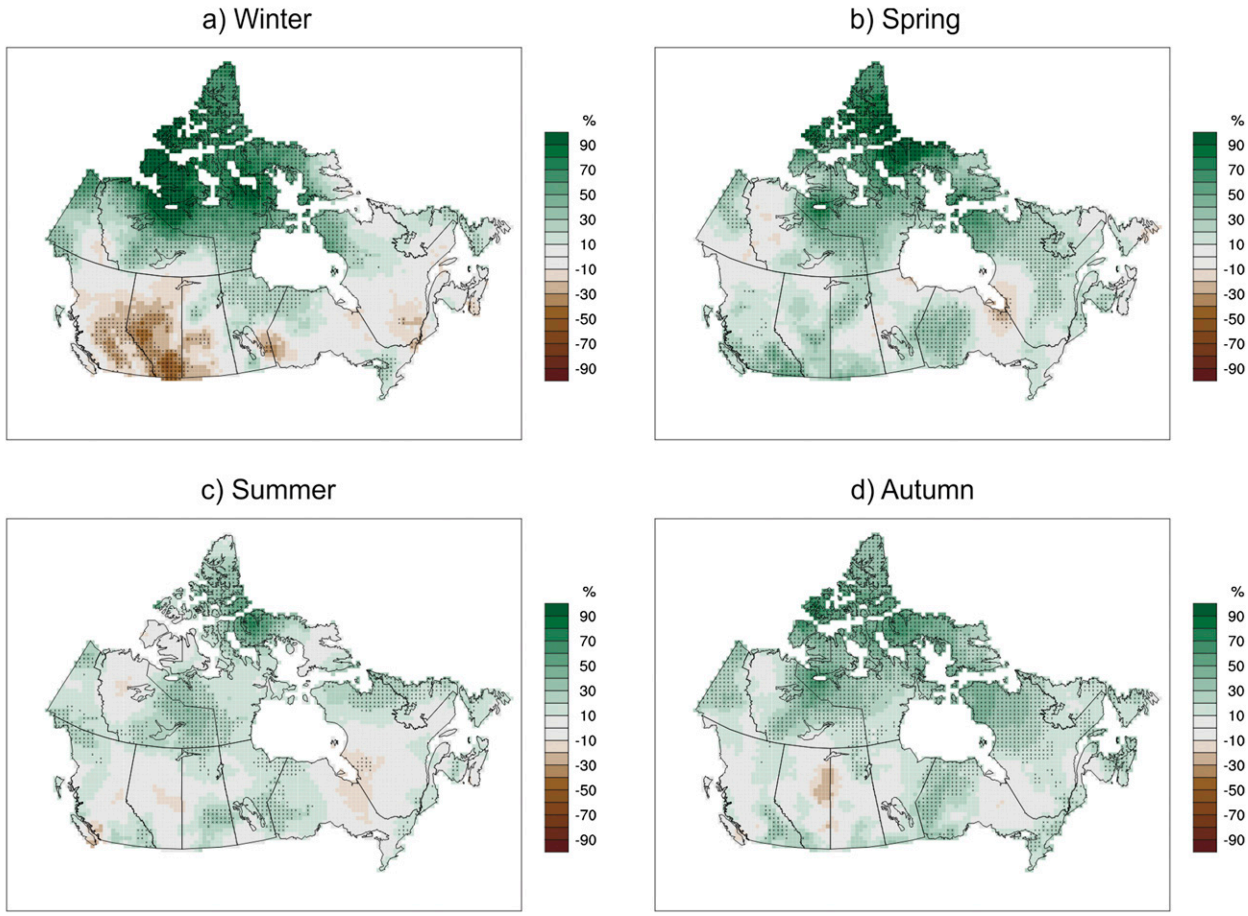


FIG. 5. Trends in total precipitation for 1948–2012 for (a) winter, (b) spring, (c) summer, and (d) autumn. Grid squares with trends statistically significant at the 5% level are marked with a dot. The units are percentage per 65 yr.

The annual maximum snow depth shows a general tendency toward smaller values (Fig. 8c). A decrease of 4 cm [3–11 cm] during 1950–2012 is found when the anomalies are averaged over the 104 stations: of these, 23% exhibit a significant decrease of more than 20 cm. The decrease in the maximum snow depth in the southern regions is being driven by less winter precipitation (Fig. 5a) and a lower fraction of precipitation falling as snow from the winter warming (Fig. 3a). Significant trends toward earlier dates of maximum snow depth are observed at 26% of the stations (Fig. 8d). The data also indicate that, when averaged over the 104 stations, the annual maximum snow depth occurs earlier in the year by about 13 days [6–21 days]. These results are consistent with winter warming. They are also in agreement with broad-scale trends toward declining spring snowpack and earlier runoff over the northwestern United States (Mote 2006; Barnett et al. 2008).

### d. *Trends in streamflow*

Evidence of significant change is mainly found in April mean streamflow and in the starting date of high-flow season over 1950–2012. The results show significant increasing trends in April mean streamflow at 25% of the sites (Fig. 9a) and significant decreasing trends in the starting date of the high-flow season at 21% of the sites (Fig. 9b), mostly located in the western and eastern parts of the country. The trends toward earlier high-flow season and increase in April mean streamflow were previously documented in Zhang et al. (2001) and are consistent with the trends found across western North America (Stewart et al. 2005; Brabets and Walvoord 2009). The earlier start of spring freshet and increasing streamflow in April may be attributed to a combination of several factors, including earlier spring snowmelt and an increased proportion of liquid precipitation, depending on location. However, they are also dependent

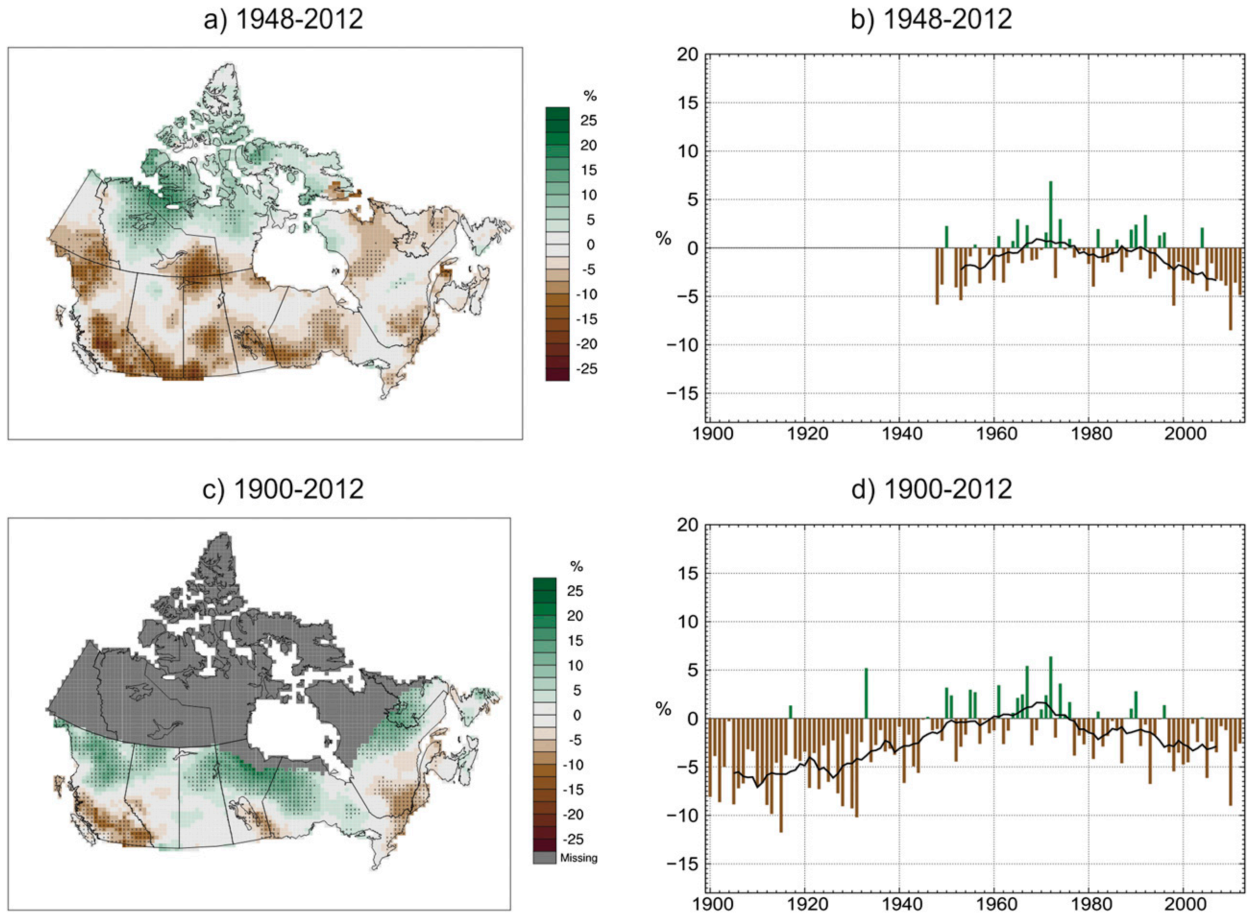


FIG. 6. Trends in annual snowfall ratio for (a) 1948–2012 [% $(65\,\mathrm{yr})^{-1}$] and (c) 1900–2012 [% $(113\,\mathrm{yr})^{-1}$]. Grid squares with trends statistically significant at the 5% level are marked with a dot. Annual snowfall ratio for (b) Canada (1948–2012) and (d) southern Canada (1900–2012). The black line is an 11-yr running mean.

on the maximum water storage of the snowpack and any changes in the distribution of the runoff. A recent study suggests that a shift in precipitation from snow toward rain does not necessary lead to increasing streamflow overall (Berghuijs et al. 2014).

Analysis of the date of river ice breakup and freezeup indicate some evidence of trends toward earlier river ice breakup at most locations for 1950–2012 (Fig. 9c) and 1967–2012. There is less evidence of changes in the date of river ice freezeup (not shown). These results are consistent with previously published studies (Duguay et al. 2006; Latifovic and Pouliot 2007) that report widespread trends to earlier spring breakup with strong regional variability in freezeup dates. These trends are consistent with warmer spring temperature and earlier start of the spring freshet. They are also in agreement with the trends observed over shorter periods of time (Zhang et al. 2001; Bonsal et al. 2006).

## 5. Influence of large-scale oscillation indices on observed trends

### *a. Influence of the PDO and NAO indices on temperature trends*

The regression coefficients associated with the PDO and NAO are first examined when the model is fitted for 1948–2012. The coefficients are significant for a higher number of grid points in winter and spring than in summer and autumn. Significant positive coefficients for PDO are found in the west (Figs. 10a,d), while significant negative coefficients for NAO are observed in the northeast (Figs. 10b,e). These results are consistent with those presented in previous studies (Liu et al. 2007; Wang et al. 2005; Bonsal et al. 2001), which showed positive correlation between surface air temperature and PDO in the west and negative correlation between surface air temperature and NAO in the northeast. The

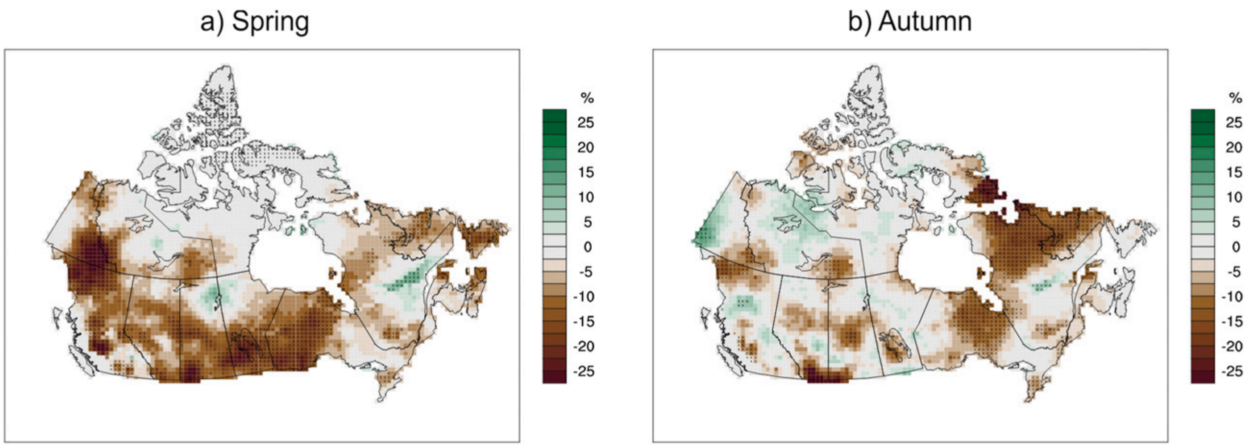


FIG. 7. Trends in snowfall ratio for 1948–2012 for (a) spring and (b) autumn. Grid squares with trends statistically significant at the 5% level are marked with a dot. The units are percentage per 65 yr.

combination of the PDO and NAO indices explain about 21% (13%) of the variation in winter (spring) mean temperature in Canada during 1948–2012 (this percentage is calculated at each grid point and averaged over the nation). This percentage is much smaller for summer and autumn.

When the trends in the residuals are assessed for 1948–2012, the winter and spring warming (Figs. 10c,f) is

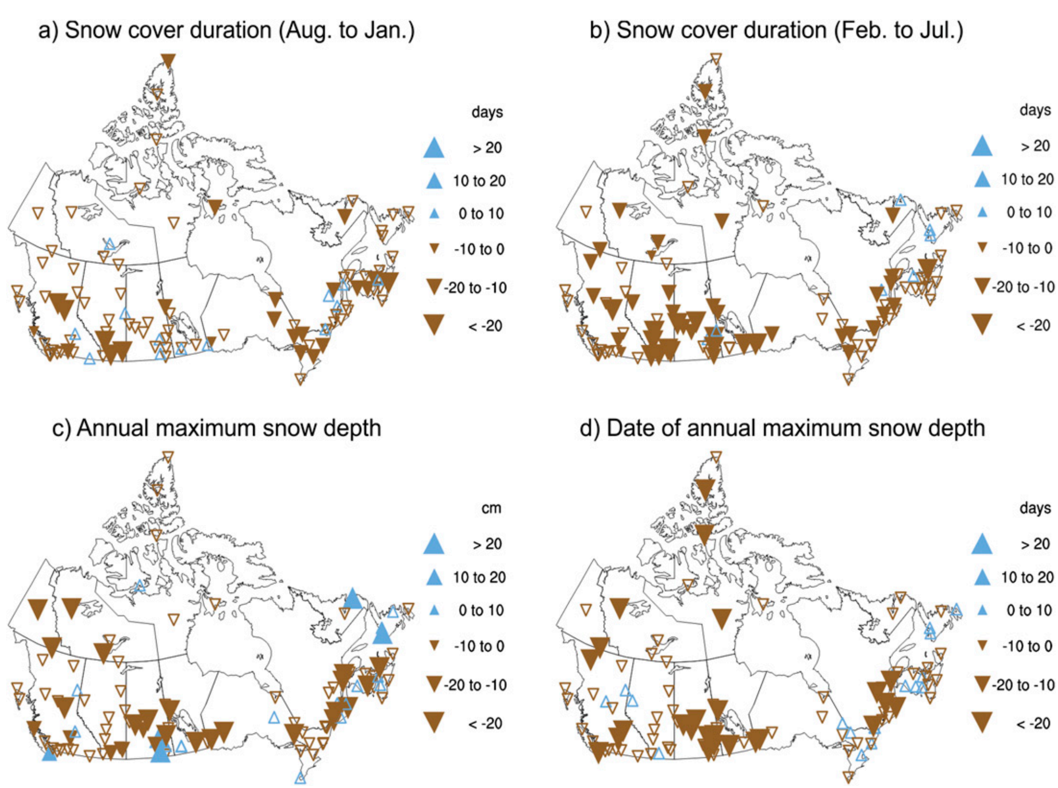


FIG. 8. Trends in snow cover data for 1950–2012: snow-cover duration (number of days with snow on the ground ≥ 2 cm) during (a) the first half of the snow season (August–January) and (b) the second half of the snow season (February–July); (c) annual maximum snow depth; and (d) date of annual maximum snow depth. Upward (downward) pointing triangles indicate positive (negative) trends. Solid triangles correspond to trends significant at the 5% level.

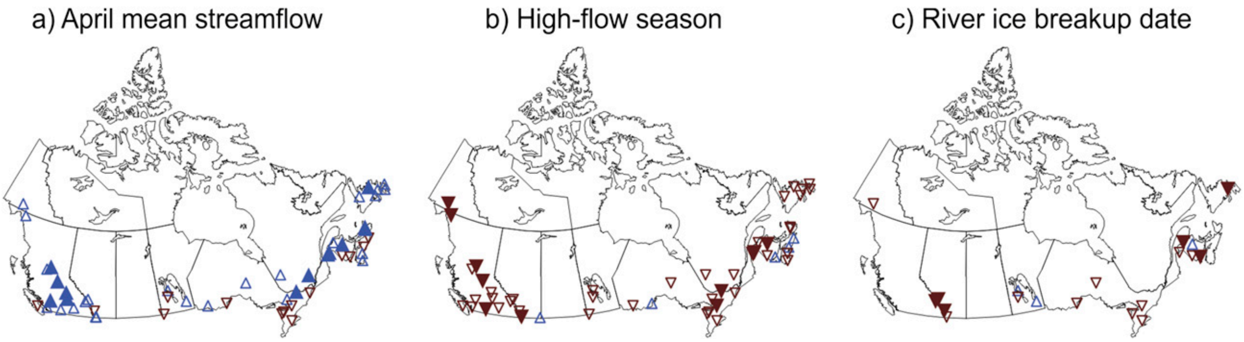


FIG. 9. Trends in (a) April mean streamflow, (b) starting date of high-flow season, and (c) date of river ice breakup for 1950–2012. Upward (downward) pointing triangles indicate positive (negative) trends. Solid triangles correspond to trends significant at the 5% level.

less pronounced than the warming observed in the original data (Figs. 3a,b), mainly in the western and central regions. However, the trends are still significant in many regions and their magnitude is more consistent across the country. The winter (spring) time series of the residuals averaged over the nation indicate a significant warming of 2.1°C (1.0°C) over the past 65 yr while the original winter (spring) data show a significant increase of 3.3°C (1.8°C). These results demonstrate that, while the oscillations explain some of the temperature variations over 1948–2012, the observed trends cannot be explained by low-frequency variability modes alone since there is still significant warming after removing the effects of the PDO and NAO indices. The summer and autumn trends are basically the same before and after removing the influence of the oscillations.

For 1900–2012, significant positive coefficients for PDO are found in the southwest, whereas significant negative coefficients for NAO are observed over a small area in the southeast, during winter and spring (figures not presented). The PDO and NAO indices explain only 16% (10%) of the variation in winter (spring) mean

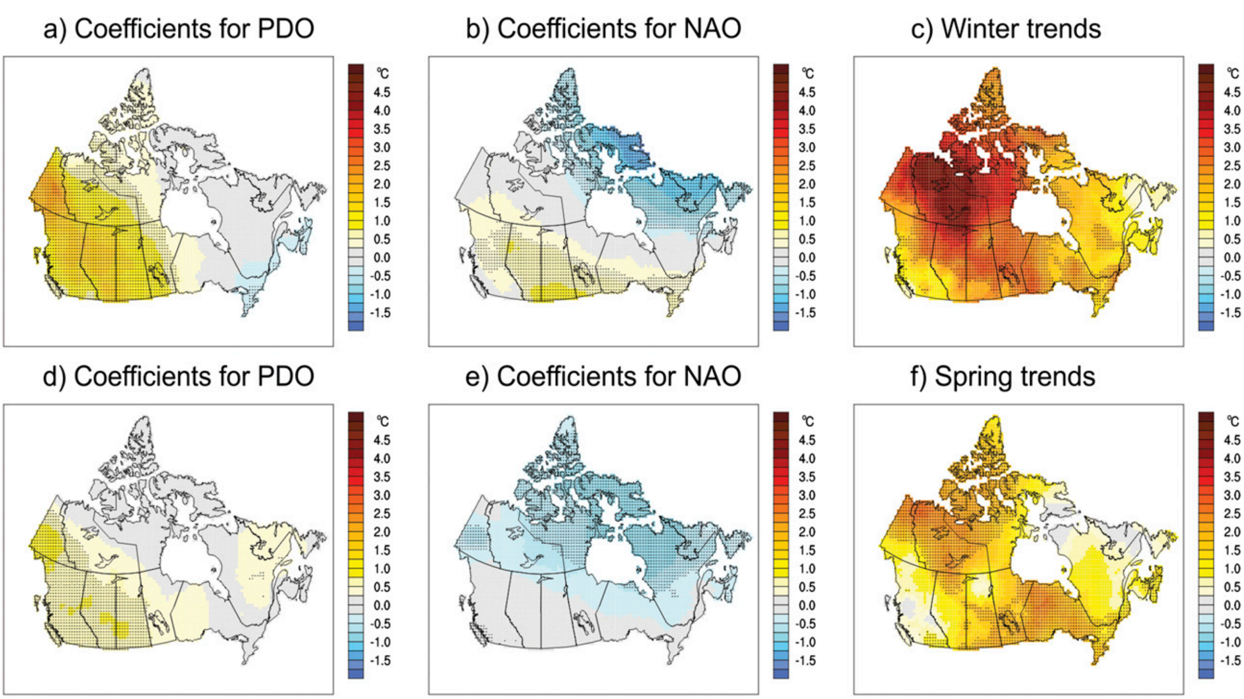


FIG. 10. Regression coefficients for (a) PDO and (b) NAO when the model is fitted to winter mean temperature. (c) Trends in winter mean temperature for 1948–2012 after removing the influence of PDO and NAO. Regression coefficients for (d) PDO and (e) NAO when the model is fitted to spring mean temperature. (f) Trends in spring mean temperature for 1948–2012 after removing the influence of PDO and NAO. Grid squares with trends (or coefficients) statistically significant at the 5% level are marked with a dot. The units are degrees Celsius per 65 yr.

temperature in southern Canada during 1900–2012. The temperature trends after removing the influence of the PDO and NAO indices are almost identical to those observed in the original data (Fig. 2c). The winter (spring) time series of the residuals averaged over the southern Canada indicate a significant warming of 2.5°C (1.8°C) over the past 113 yr, while the original winter (spring) data show a significant increase of 2.6°C (1.9°C). The results indicate that the influence of the PDO and NAO oscillations on the observed temperature trends is very small in southern Canada over the past 113 yr. They also suggest that the magnitude of the trends is more similar over both periods of time after removing the influence of the oscillations. In particular, the winter mean temperature has increased by 2.1°C in Canada for 1948–2012 while it has increased by 2.5°C in southern Canada for 1900–2012 after removing the effects of the oscillations (although the area covered is different).

### b. *Influence of NPI and NAO (or PDO and AMO) on temperature trends*

Annual and seasonal mean temperature trends are also examined after removing the influence of the atmospheric (NPI and NAO) and oceanic (PDO and AMO) oscillations separately. The resulting trends for 1948–2012 and 1900–2012 are similar to those obtained when the effects of the PDO and NAO are taken into account. In winter and spring, significant negative coefficients for NPI are mainly found in the western and central regions and significant negative coefficients for NAO prevail in the northeast (figures not presented). For the same seasons, significant positive coefficients for AMO are found in the central and eastern regions whereas significant positive coefficients for PDO prevail in the west. The 1948–2012 trends in winter and spring mean temperatures after removing the effects of NPI and NAO (PDO and AMO) are very similar to those presented in Figs. 10c,f. Overall, these results indicate that the warming is still significant and more consistent across the country after removing the influence of the large-scale oscillations. They also suggest that the observed temperature trends cannot be explained by low-frequency variability modes alone.

### c. *Influence of PDO and NAO on the trends in other climate elements*

Annual and seasonal total precipitation and snowfall ratio trends are assessed after removing the influence of the PDO and NAO indices. The combination of the PDO and NAO explain less than 10% of the variation in these two elements for 1948–2012 and 1900–2012. The regression coefficients are significant for a greater number of grid points for winter precipitation and spring snowfall ratio during 1948–2012. For winter precipitation, significant negative coefficients for PDO are found in the south (Fig. 11a) and significant negative coefficients for NAO are found in the northeast (Fig. 11b). The trends in winter precipitation for 1948–2012 after removing the effect of the oscillations (Fig. 11c) are similar to those obtained from the original data (Fig. 5a) with the exception of weaker decreasing trends in the southwest. For spring snowfall ratio, significant negative coefficients for PDO prevail in the west (Fig. 11d), whereas coefficients for NAO are generally near zero (Fig. 11e). The trends in spring snowfall ratio for 1948–2012 after removing the influence of PDO and NAO (Fig. 11f) are similar to those obtained from the original data (Fig. 7a), with the exception of less extensive decreasing trends in the west. The results indicate that, while the PDO index explains some of the variations in winter precipitation and spring precipitation falling as snow during 1948–2012, the magnitude and significance of the trends do not change very much after removing the influence of the PDO and NAO for 1948–2012. There is no evidence of the PDO and NAO impact on the precipitation and snowfall ratio trends during 1900–2012.

When the trends are assessed for various snow-cover and streamflow indices, the regression coefficients associated with the PDO and NAO are significant at a few stations only. The trends after removing the effects of PDO and NAO are almost identical to those obtained from the original values (Figs. 8 and 9). There is no evidence that the PDO and NAO are affecting the trends in the snow-cover and streamflow indices by very much during 1950–2012 (although the number of stations used in this study is limited).

## 6. Summary and discussion

The trend results reported in this study present a picture of a changing climate in Canada which is consistent across multiple climate elements. Over the past six decades, surface air temperature has increased in Canada, with the largest warming occurring in winter and spring. Precipitation totals have increased principally in the north in all seasons. Winter precipitation has decreased in the southwest and there have been widespread decreases in the amount of precipitation falling as snow in the south. These changes in temperature and precipitation have led to a shorter snow-cover season, mainly in response to earlier snowmelt (in all regions) and lower snowfall amounts (in southern regions). A shorter snow accumulation period and reduced snowfall amounts has resulted in a decrease in annual maximum snow accumulations and earlier dates of maximum snow

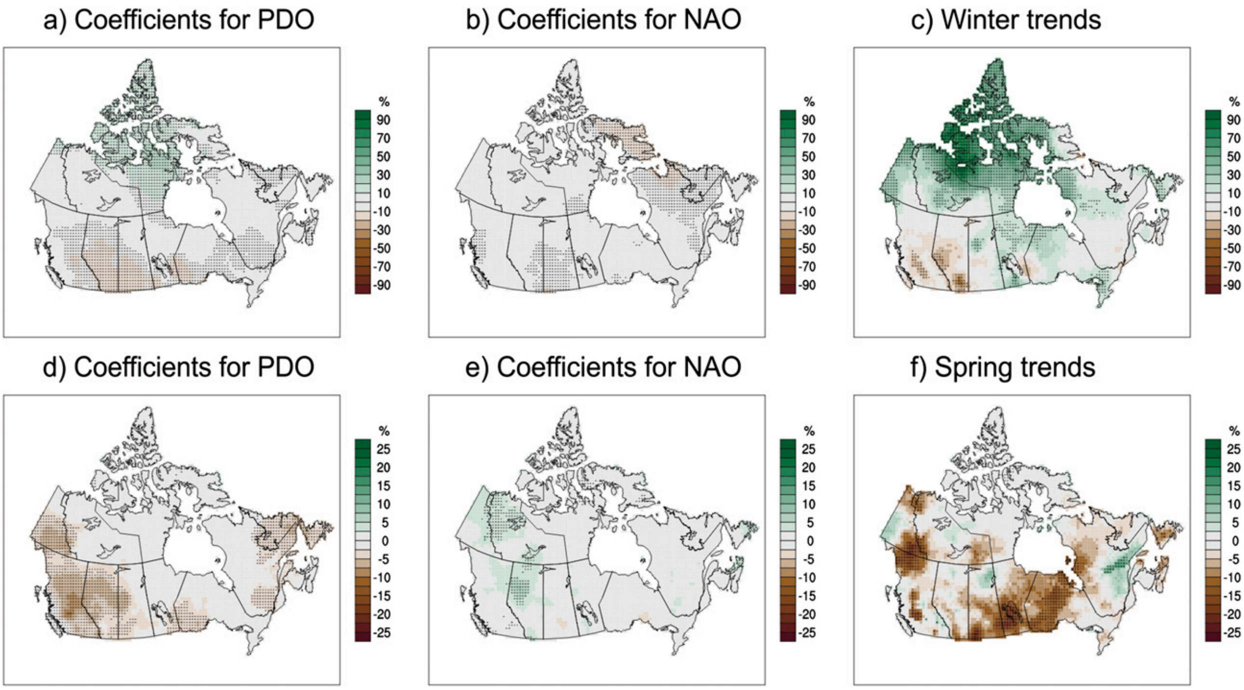


FIG. 11. Regression coefficients for (a) PDO and (b) NAO when the model is fitted to winter precipitation. (c) Trends in winter precipitation for 1948–2012 after removing the influence of PDO and NAO. Regression coefficients for (d) PDO and (e) NAO when the model is fitted to spring snowfall ratio. (f) Trends in spring snowfall ratio for 1948–2012 after removing the influence of PDO and NAO. Grid squares with trends (or coefficients) statistically significant at the 5% level are marked with a dot. The units are percentage per 65 yr.

depth at many stations. An observed earlier start of spring freshet and increasing streamflow in April are consistent with earlier spring snowmelt because of winter and spring warming. Over the past century, temperature has increased in southern Canada, but the rate of increase was not consistent and included a modest cooling during 1940–70. During the same period, the precipitation has increased almost everywhere across the region and the amount of precipitation falling as snow has increased north of 55°N and decreased in the south.

When the influence of large-scale oscillations is taken into account, the warming observed in Canada during 1948–2012 is slightly reduced in the western regions, especially during winter and spring, but the temperature trends are still significant and the warming is more consistent across the country. There are less decreasing trends in winter precipitation totals and spring precipitation falling as snow during 1948–2012 in the southwest after removing the effects of the oscillations, but the overall pattern of increasing winter precipitation trends in the north and decreasing spring snowfall ratio trends in the south remains the same. There is no evidence that the large-scale oscillations have influenced the temperature and precipitation trends over 1900–2012 and the snow-cover and streamflow indices trends over 1950–2012. These results clearly demonstrate that, while the oscillations explain some of the climate variations during 1948–2012, the observed temperature and precipitation trends cannot be explained by low-frequency variability modes alone. Other factors, external to the climate system, such as increase in greenhouse gases and aerosols in the atmosphere may have played a significant role in the observed changes in climate (Wan et al. 2015; Gillett et al. 2008; Min et al. 2008a; Zhang et al. 2006). Ongoing work involves the comparison of the changes observed in historical data with those simulated by climate models under various external forcing and the results will be reported in a different study.

This study presents an analysis of trends in several climate elements using the best updated data available over similar periods of time in order to highlight the consistencies among the trends in related climate variables. It is important to closely monitor climate change in order to improve our understanding regarding the various mechanisms responsible for climate variations. Canada's climate shows multidecadal-scale variability over the past century associated with low-frequency atmospheric and oceanic oscillations. This study reports, for the first time, climate trends in Canada after removing potential mechanisms representing low-frequency variations. The results show that large-scale atmospheric and oceanic oscillations have influenced regional climate trends to some extent. However, it also reveals that these indices alone do not explain long-term changes observed in various climate elements in Canada.

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