Canadian climate trends, 1950-2007

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PREFACE

The Canadian Councils of Resource Ministers developed a Biodiversity Outcomes Framework[1] in 2006 to focus conservation and restoration actions under the *Canadian Biodiversity Strategy*.[2] *Canadian Biodiversity: Ecosystem Status and Trends 2010*[3] was a first report under this framework. It assesses progress towards the framework's goal of "Healthy and Diverse Ecosystems" and the two desired conservation outcomes: i) productive, resilient, diverse ecosystems with the capacity to recover and adapt; and ii) damaged ecosystems restored.

The 22 recurring key findings that are presented in *Canadian Biodiversity: Ecosystem Status and Trends 2010* emerged from synthesis and analysis of technical reports prepared as part of this project. Over 500 experts participated in the writing and review of these foundation documents. This report, *Canadian climate trends, 1950-2007*, is one of several reports prepared on the status and trends of national cross-cutting themes. It has been prepared and reviewed by experts in the field of study and reflects the views of its authors.

Acknowledgements

The authors gratefully acknowledge the helpful comments received from the reviewers of this report and the patience of the ESTR staff during the long and sometimes arduous process of generating the final figures.

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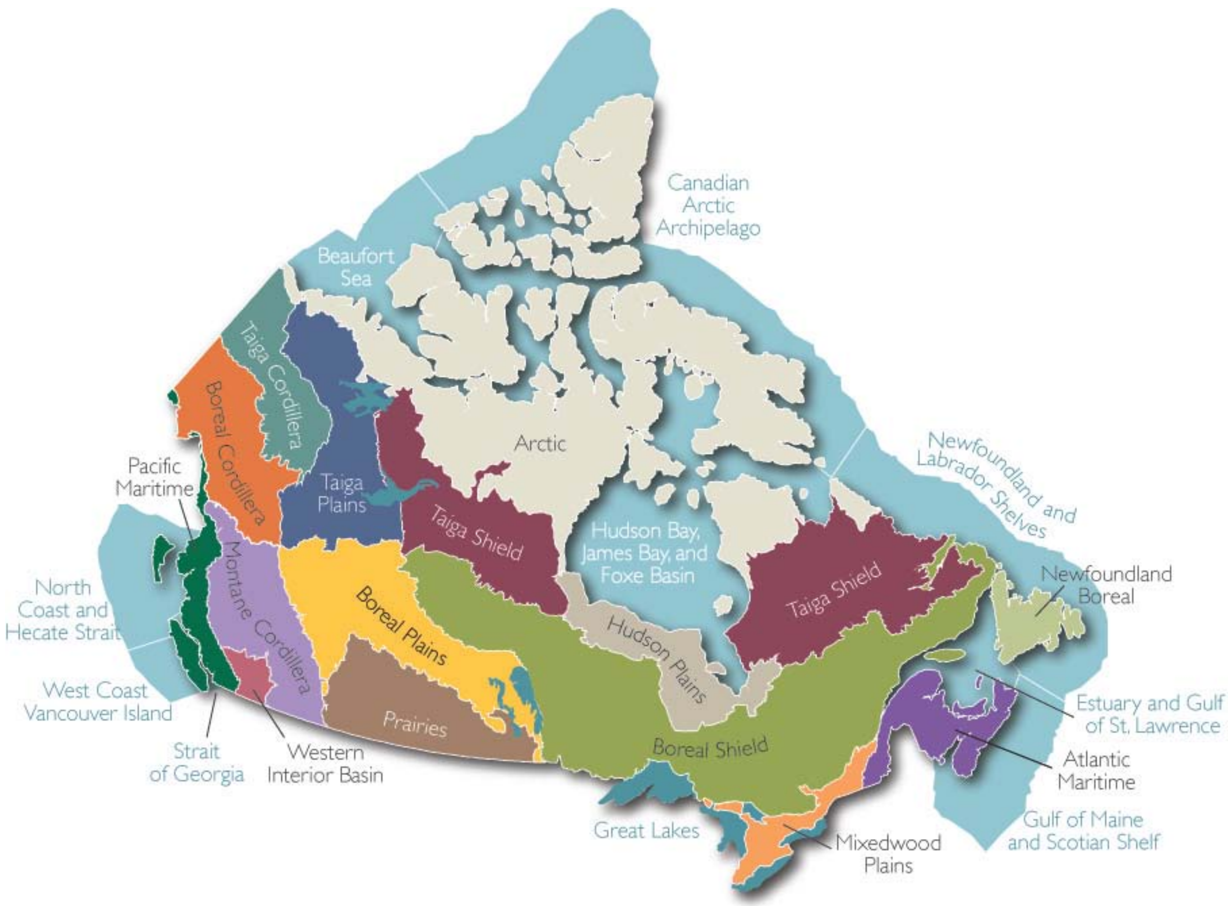
[1] Environment Canada. 2006. Biodiversity outcomes framework for Canada. Canadian Councils of Resource Ministers. Ottawa, ON. 8 p. http://www.biodivcanada.ca/default.asp?lang=En&n=F14D37B9-1

[2] Federal-Provincial-Territorial Biodiversity Working Group. 1995. Canadian biodiversity strategy: Canada's response to the Convention on Biological Diversity. Environment Canada, Biodiversity Convention Office. Ottawa, ON. 86 p. http://www.biodivcanada.ca/default.asp?lang=En&n=560ED58E-1

[3] Federal, Provincial and Territorial Governments of Canada. 2010. Canadian biodiversity: ecosystem status and trends 2010. Canadian Councils of Resource Ministers. Ottawa, ON. vi + 142 p. http://www.biodivcanada.ca/default.asp?lang=En&n=83A35E06-1

Ecological Classification System – Ecozones+

A slightly modified version of the Terrestrial Ecozones of Canada, described in the *National Ecological Framework for Canada*,[4] provided the ecosystem-based units for all reports related to this project. Modifications from the original framework include: adjustments to terrestrial boundaries to reflect improvements from ground-truthing exercises; the combination of three Arctic ecozones into one; the use of two ecoprovinces – Western Interior Basin and Newfoundland Boreal; the addition of nine marine ecosystem-based units; and, the addition of the Great Lakes as a unit. This modified classification system is referred to as "ecozones+" throughout these reports to avoid confusion with the more familiar "ecozones" of the original framework.[5]



[4] Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch. Ottawa/Hull, ON. 125 p. Report and national map at 1:7 500 000 scale.

[5] Rankin, R., Austin, M. and Rice, J. 2011. Ecological classification system for the ecosystem status and trends report. Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 1. Canadian Councils of Resource Ministers. Ottawa, ON. http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-0

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INTRODUCTION

Climate is the long-term behaviour of weather. It includes not only average conditions of weather, but also variations and extremes. Just as weather differs from one day to another, climate also fluctuates from one period to another. Therefore, climate naturally shifts as it does when ice ages come and go. Over the past 100 years, the world's climate has changed noticeably. Unlike the natural variation in the climate, however, the climate change observed over the past century contains a significant and detectable human-induced component (Intergovernmental Panel on Climate Change, 2007). It is also changing at a faster rate than experienced before, and faster than some ecosystems are able to adapt. In fact, widespread changes in the temperature and other aspects of the climate system are now affecting many physical and biological systems on all continents (Intergovernmental Panel on Climate Change, 2007). Canada's climate has also experienced rapid changes in temperature, precipitation, hydrometeorologic regimes, and snow and ice cover over recent decades, with important implications for ecosystems.

The trends in this report were prepared as background material for *Canadian Biodiversity: Ecosystem Status and Trends 2010.* In addition to this overview report, trends for regionally-averaged climate variables were prepared for each terrestrial Technical Ecozone+ Report. It should be noted that the objective of this report was to provide information on the rate and spatial character of changes in important climate variables over Canada, rather than an assessment of the impacts of climate change. Trends in climate extremes have been analyzed and published recently, and the relevant publications are referenced in this report. The material presented in this report is preliminary. More in-depth analysis and stronger emphasis on the understanding the causes of the observed climate variability and trends is being prepared for journal publication.

DATA

Climate data are records of observed climate conditions. They are taken at specific sites and times with particular instruments under a set of standard procedures. A climate dataset, therefore, reflects not only climate condition, but also other non-climate-related factors such as where and how the observations have been taken. For example, a change in observing procedures and/or instrumentation can introduce a non-climatic change in the data series. These artefacts in the climate data are removed, as much as possible, through the creation of homogenized data series in order to provide reliable assessments of climate trends. Trends presented in this report are largely based on homogenized data.

The temperature data used in the analysis were from 210 relatively evenly distributed stations across the country that had been rigorously checked and corrected for known sources of systematic error (such as station shifts, changes in observing procedures, and excluding stations with strong urban warming effects) (Vincent, 1998). This dataset has been used in previous studies of changes in Canadian temperature and its extremes (Zhang et al., 2000; Bonsal et al., 2001; Vincent and Mekis, 2006). Trend information was computed over the period 1950 to 2007, and daily mean temperatures were computed from the average of the daily minimum and maximum temperature.

The precipitation data used include adjusted daily rainfall and snowfall amounts observed at 495 stations across the country (Mekis and Hogg, 1999). All known inhomogeneities in the station data caused by changes in location and precipitation measurement programs were carefully minimized: wind undercatch, wetting loss, evaporation, trace events, and varying snow densities were also considered in the adjustment procedure. A subset of this dataset has been used in other studies to investigate changes in heavy precipitation events in Canada (Zhang et al., 2001b) and trends in precipitation intensity in Canada (Vincent and Mekis, 2006). The variables selected for trend analysis were annual and seasonal precipitation totals, the fraction of annual precipitation falling in solid form (expressed as a percentage), and the number of days with measureable precipitation (greater than trace amounts).

Information on trends and variability in snow cover were derived from daily snow depth observations made at climate and synoptic stations. Daily snow depth observations from manual ruler measurements have been made at most Canadian synoptic stations since about the mid-1950s. The daily observing program was extended to climatological (cooperative) stations in the early 1980s, approximately quadrupling the number of stations in the Canadian network to about 2000. However, there are only about 150 stations with more-or-less complete data from 1950 to 2007 for monitoring changes in snow cover conditions in Canada. The data for this report were taken from a recent update of the Canadian Snow CD (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). Only stations with 47 years or more of data were included in the analysis and trends were computed over 57 snow seasons from 1950/51 to 2006/07. It should be noted that most of the daily snow depth observations are made at open sites in or near populated regions and may not be representative of the surrounding snow cover, particularly in regions with higher terrain (such as British Columbia and Alberta) and forest cover, as snow in open terrain tends to melt out faster than snow in vegetated areas. The station distribution is also strongly biased toward southern latitudes with major data gaps in areas above about 55°N. The snow cover variables presented in this report are snow cover duration (SCD) defined as the number of days with 2 cm or more of snow on the ground from an August to July snow year, and the annual maximum snow depth. SCD is computed over the fall (August to January) and spring (February to July) halves of the snow year to provide information on changes in the onset and melt dates of snow cover. An assessment of the homogeneity of daily snow depth observations was carried out by Brown and Braaten (1998) with little evidence of detectable inhomogeneities.

The timing of ice formation and thaw on water bodies are important indicators of climate condition. Tracking and analyzing these "ice-on" and "ice-off" events is known as ice phenology. Historical Canadian ice phenology data are archived in the Canadian Lake Ice Database developed by Lenormand et al. (2002) based on ice observation programs managed by the Meteorological Service of Canada and the Canadian Ice Service. Some additional data has been added from the volunteer IceWatch program (IceWatch, 2008b). While there are a large number of observations in the database, there are relatively few sites with continuous observations spanning several decades suitable for trend analysis, and observing programs ceased at many sites during the 1990s. This report therefore draws extensively on the results of published trend analyses of Canadian ice phenology data provided by Zhang et al. (2001a) and Duguay et al. (2006) and, more recently, the analysis of Latifovic and Pouliot (2007) who used visible satellite imagery to extend the ice phenology record at about 40 lake sites across Canada.

The availability of water is important for ecosystems, especially in relatively dry regions. For this analysis, the Palmer Drought Severity Index (PDSI) was used as an index of water availability and was computed from observed temperature and precipitation data. The PDSI reflects changes in long-term moisture, runoff, recharge, deep percolation, and evaporation, and is useful for drought analysis over time spans of months or seasons. A positive value indicates wetness, while a negative value indicates dry condition. PDSI modeling requires the availability of co-located and concurrent mean air temperature and total precipitation observations. For this report, PDSI was computed from the rehabilitated historical temperature and precipitation datasets described above for 80 stations with more-or-less complete temperature and precipitation data from 1950 to 2007.

The availability of heat for plant growth was investigated by calculating the number of growing degree days over the growing season. The start of the growing season was defined as the date when mean temperatures were greater than 5°C over 5 consecutive days in the spring and the end of the growing season was defined as when the inverse condition was met. The average temperature summed over this period is the number of growing degree days (a measure of accumulated heat during the growing season) and was computed at all temperature stations.

TREND ANALYSIS

In order to compare stations across different climate regions in a systematic fashion, and to make regionally averaged climate series less sensitive to changes in the spatial distribution of stations within a region over time, climate variables were expressed as anomalies with respect to a fixed 1961-1990 reference time period. In the case of temperature, the trend analysis was performed on the temperature departures (or anomalies) from the 1961-1990 reference period. For precipitation, the trend analysis was performed on the anomalies expressed as a percentage of the 1961-1990 mean. The snow cover variables were not converted to anomalies as the results were found to be insensitive to the use of anomalies or raw values.

Trends in climate series were assessed using Kendall's tau based slope estimator (Sen, 1968) following Zhang et al. (2000). This method is less sensitive to the effect outliers in the series than conventional least-squares methods, and provides more reliable assessment of statistical significance of the trend. Throughout this report, a trend is considered significant if it is statistically significant at the 5% level, and is indicated on maps with a solid triangle. The direction of the triangle indicates the sign of the trend, that is, upward-pointing triangles represent positive trends and vice versa. Trends were computed for the period 1950 to 2007 to provide the best possible spatial coverage over the country for the longest period of data coverage. There are few observations prior to 1950 in northern Canada.

It is important to note that the national maps shown here only give the strength and direction of the average change over the 1950 to 2007 period. The temporal characteristics of variability and change in the various variables over the 1950 to 2007 period are presented and discussed in each terrestrial Technical Ecozone+ Report.

Temperature

Mean daily air temperature trends are dominated by significant increases that are observed over most regions of Canada (Figure 1). The annual mean temperature has increased by about 1.4°C over the country as a whole, though the amount of temperature change differs between ecozones+. The strongest warming (>1.5°C) has occurred over western and northwestern Canada, with the lowest warming (<0.5°C) over eastern Canada. Other regions of Canada have typically experienced warming of mean annual air temperatures by 1 to 2°C.

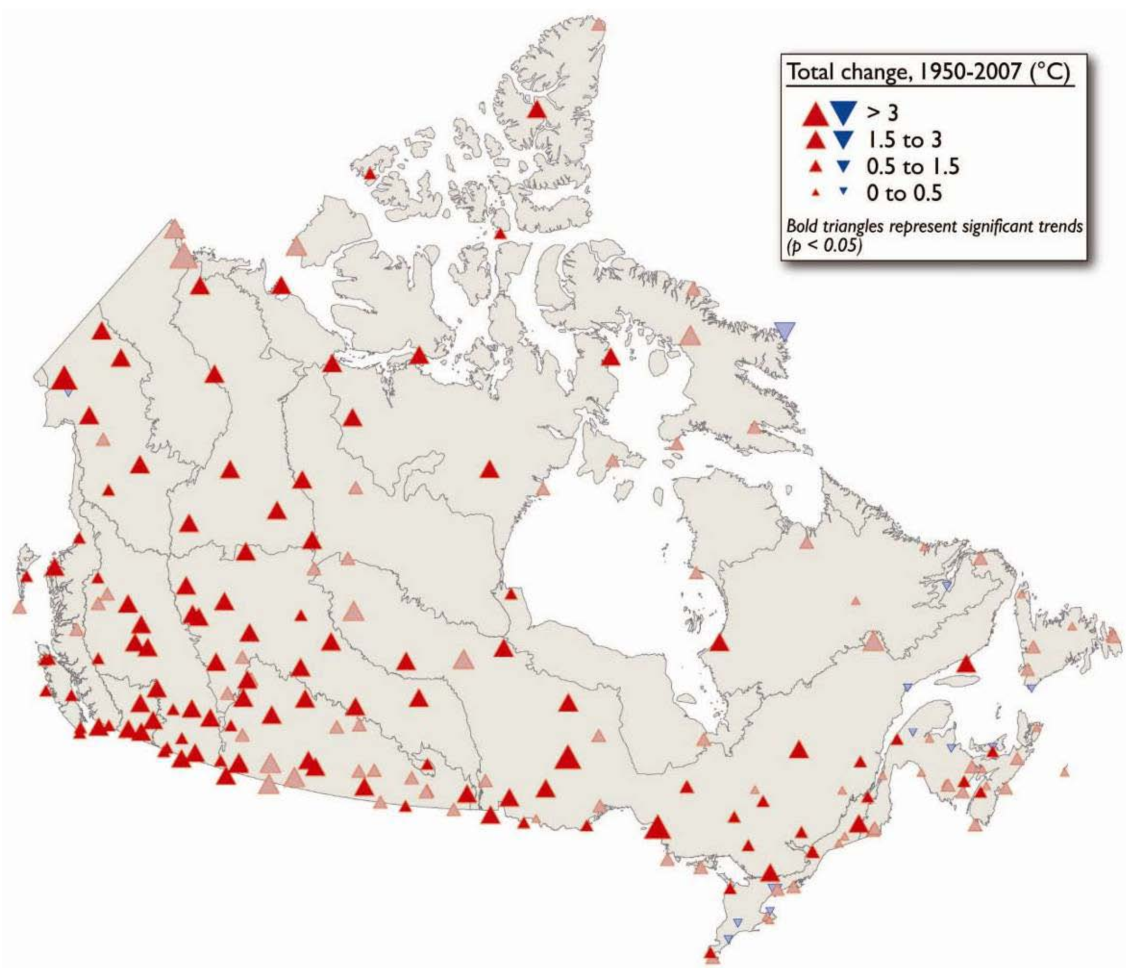

Figure 1. Change in mean annual temperature, 1950-2007.

Temperature change also differs from one season to another (Figure 2). Significant warming trends are most frequently observed in winter and spring, with significant warming concentrated over western Canada. A large number of stations show evidence of cooling in the fall but none are significant; the only stations showing significant fall trends are warming over northern Canada. Similarly, in summer the only significant trends are warming and these stations tend to be located in southern Canada. Analyses of daily temperature extremes indicate trends consistent with warming including fewer cold nights, cold days, and frost days, but more frequent warm nights and warm days (Bonsal et al., 2001; Vincent and Mekis, 2006). Zhang et al. (2006) found evidence that increases in atmospheric concentrations of greenhouse gases from human activities were making a contribution to temperature increases in Canada.

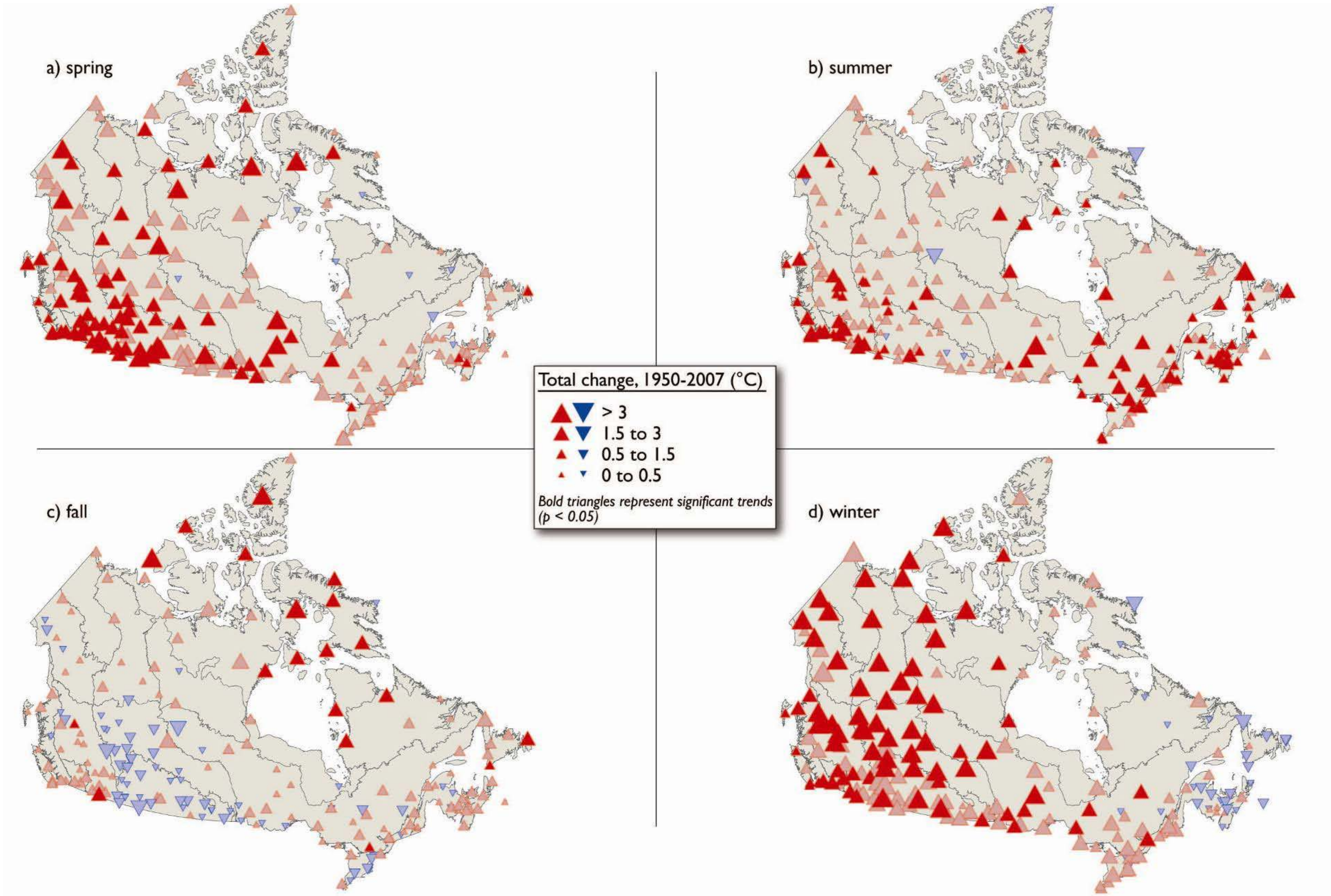

Figure 2. Change in mean temperature, 1950-2007 for a) spring (March, April, May), b) summer (June, July, August), c) fall (September, October, November), and d) winter (December, January, February).

Precipitation

Precipitation has generally increased over Canada since 1950 with the majority of stations with significant trends showing increases (Figure 3). The increasing trend is most coherent over northern Canada where many stations show significant increases. There is not much evidence of clear regional patterns in stations showing significant changes in seasonal precipitation (Figure 4) except for significant decreases which tend to be concentrated in the winter season over southwestern and southeastern Canada. Also, increasing precipitation over the Arctic appears to be occurring in all seasons except summer. The trend toward increasing precipitation has been accompanied by increases in extreme daily precipitation amounts during the growing season (Qian et al., 2010).

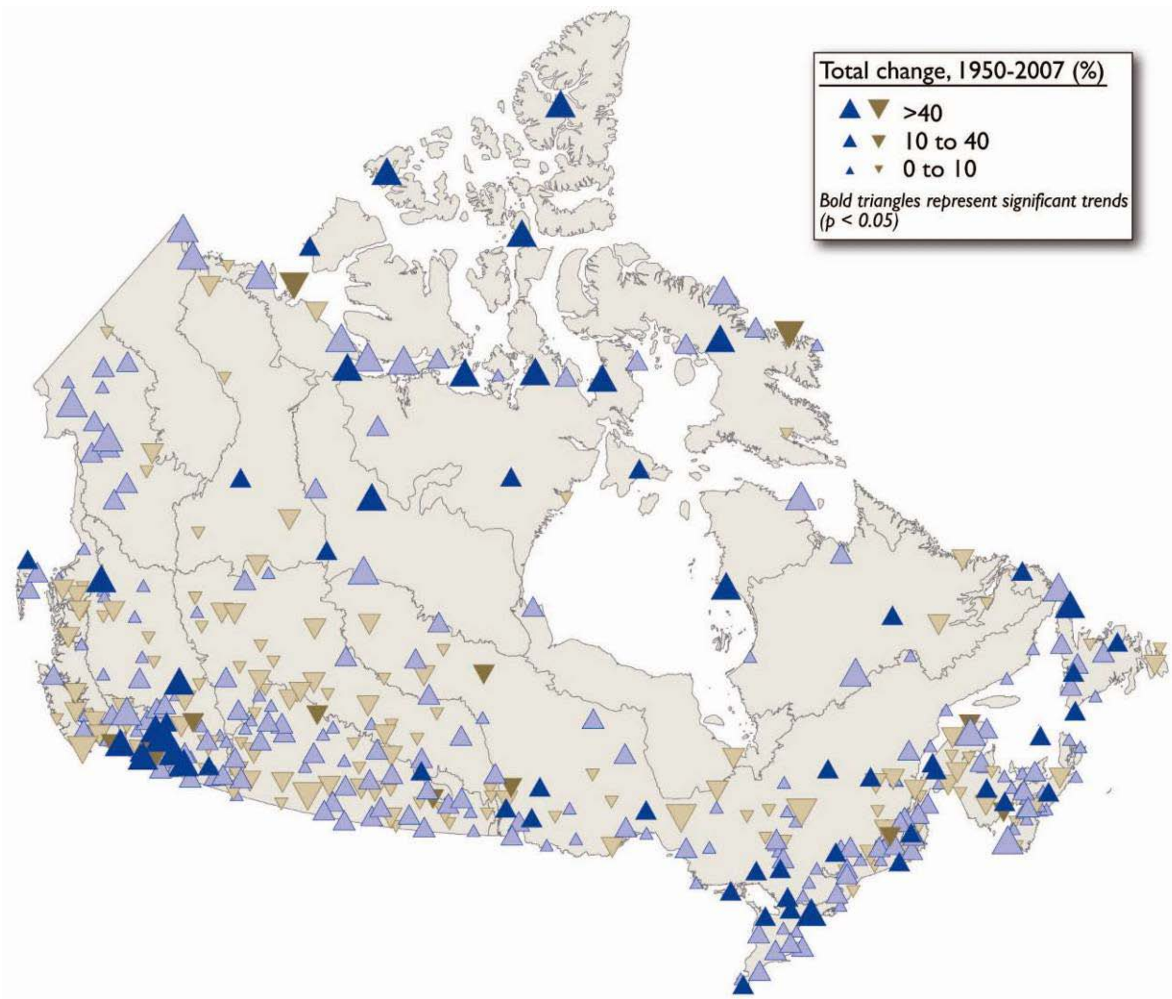

Figure 3. Change in the amount of annual precipitation, 1950-2007. Expressed as a percentage of the 1961-1990 mean.

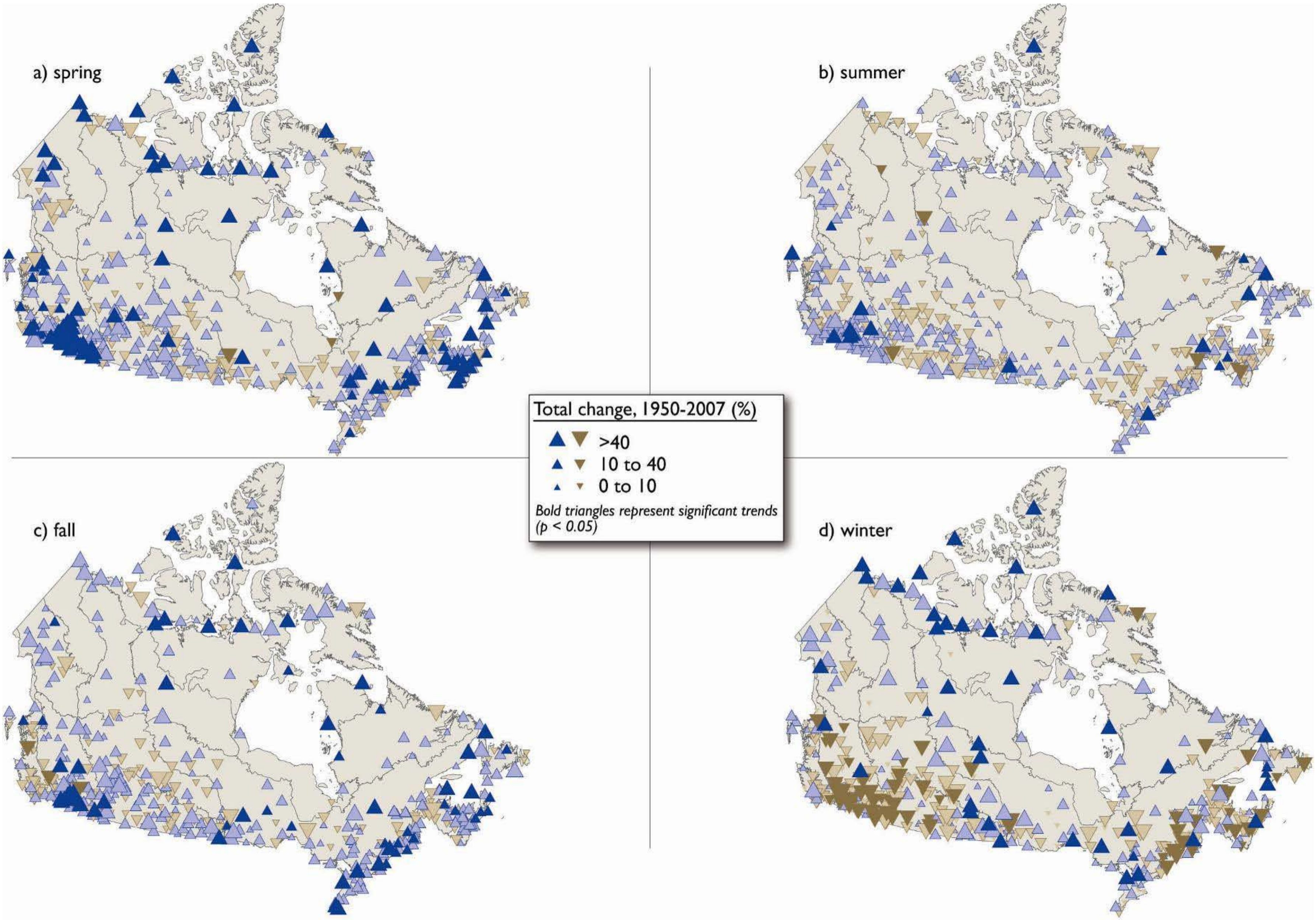

Figure 4. Change in the amount of precipitation, 1950-2007 for, a) spring (March-May), b) summer (June-August), c) fall (September-November), and d) winter (December-February).
Expressed as a percentage of the 1961-1990 mean.

Trends in the annual number of days with measurable precipitation (Figure 5) have a similar pattern to trends in total annual precipitation but with larger numbers of stations showing significant increases and decreases. This is particularly evident in summer where significant increases in the number of days with precipitation are observed over most regions of Canada (Figure 6).

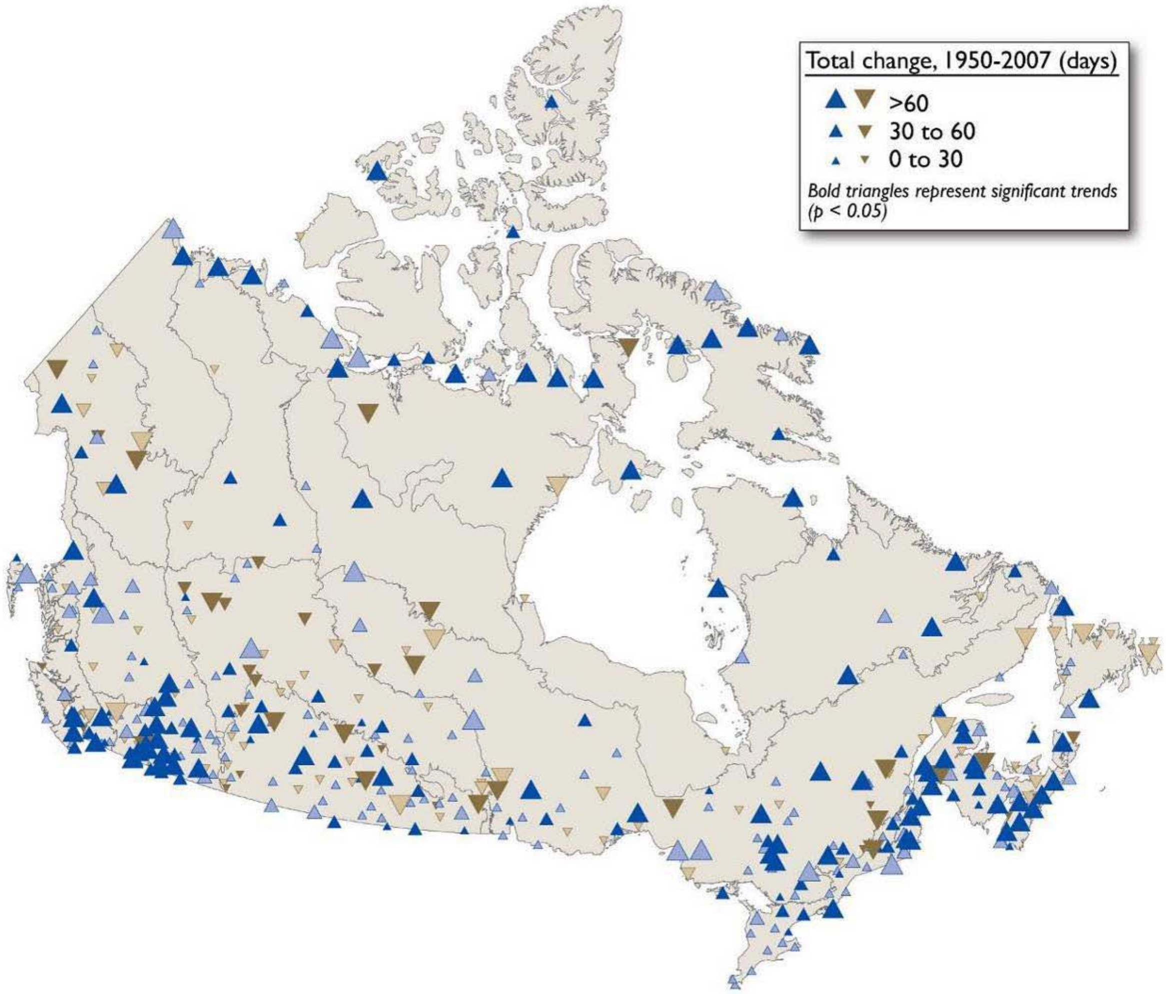

Figure 5. Change in the number of days with precipitation, 1950-2007.

It is difficult to generalize a spatial pattern in precipitation trends apart from a tendency for stations with significant increases in precipitation amount and number of days with precipitation to be located over southern coastal and northern regions of Canada. While it is not yet clear what is responsible for the precipitation changes in Canada, a recent study found evidence of anthropogenic influences in observed precipitation increases over Northern Hemispheric land areas north of 55°N including Canada (Min et al., 2008). In addition, the tendency for Arctic stations to show significant increases is consistent with climate model projections of future changes in high latitude precipitation.

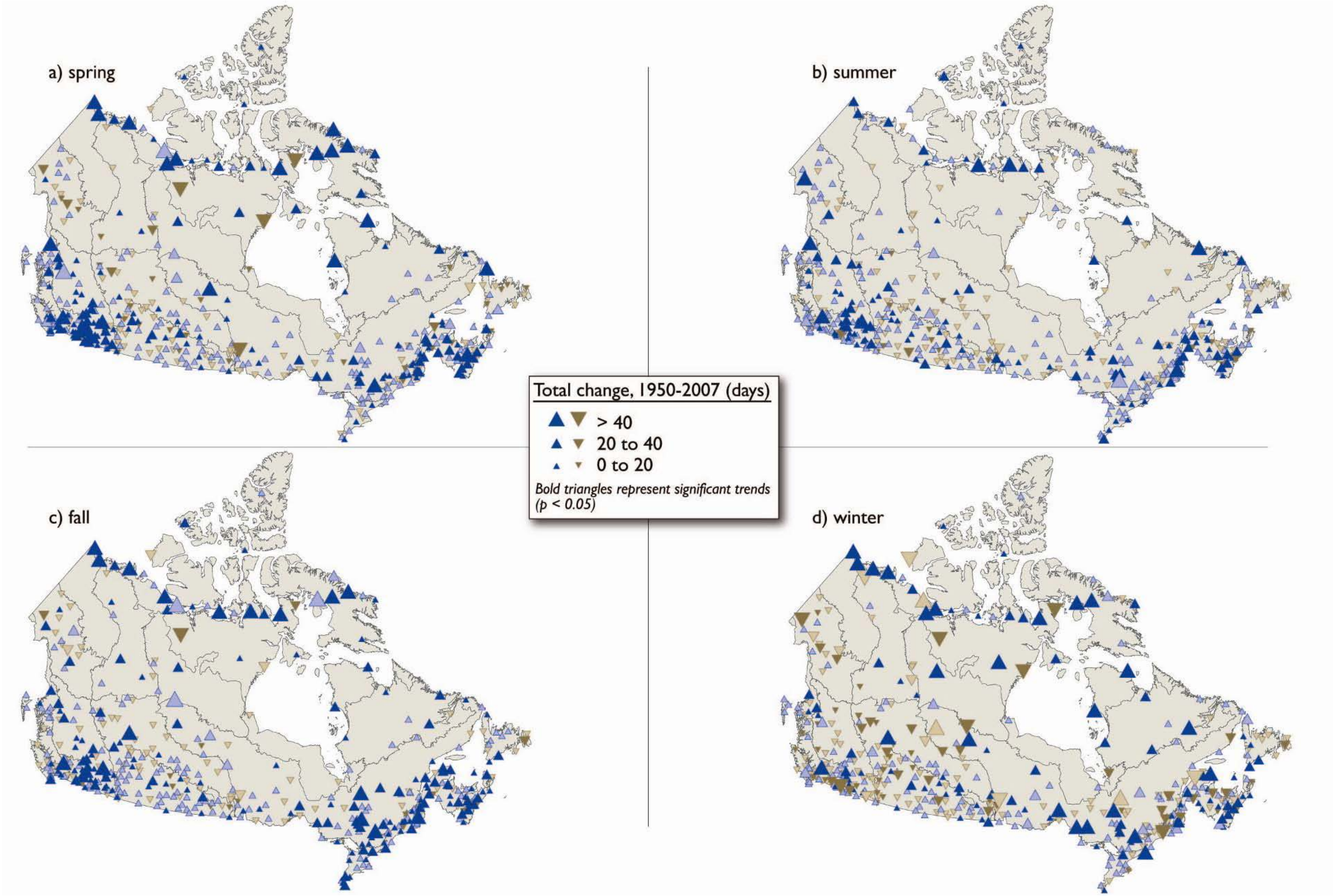

Figure 6. Change in the number of days with precipitation from 1950-2007 for a) spring (March-May), b) summer (June-August), c) fall (September-November) and d) winter (December-February).

Drought

The Palmer Drought Severity Index (PDSI) trend results for the summer season for 1950 to 2007 show that decreases dominate indicating a shift towards drier conditions (Figure 7). However, only 8 of the 80 stations analyzed showed significant changes with decreases occurring mainly over western Canada, and increases over eastern Canada. The PDSI is sensitive to both temperature and precipitation and the negative trends over western Canada are consistent with the observed summer warming seen in Figure 2.

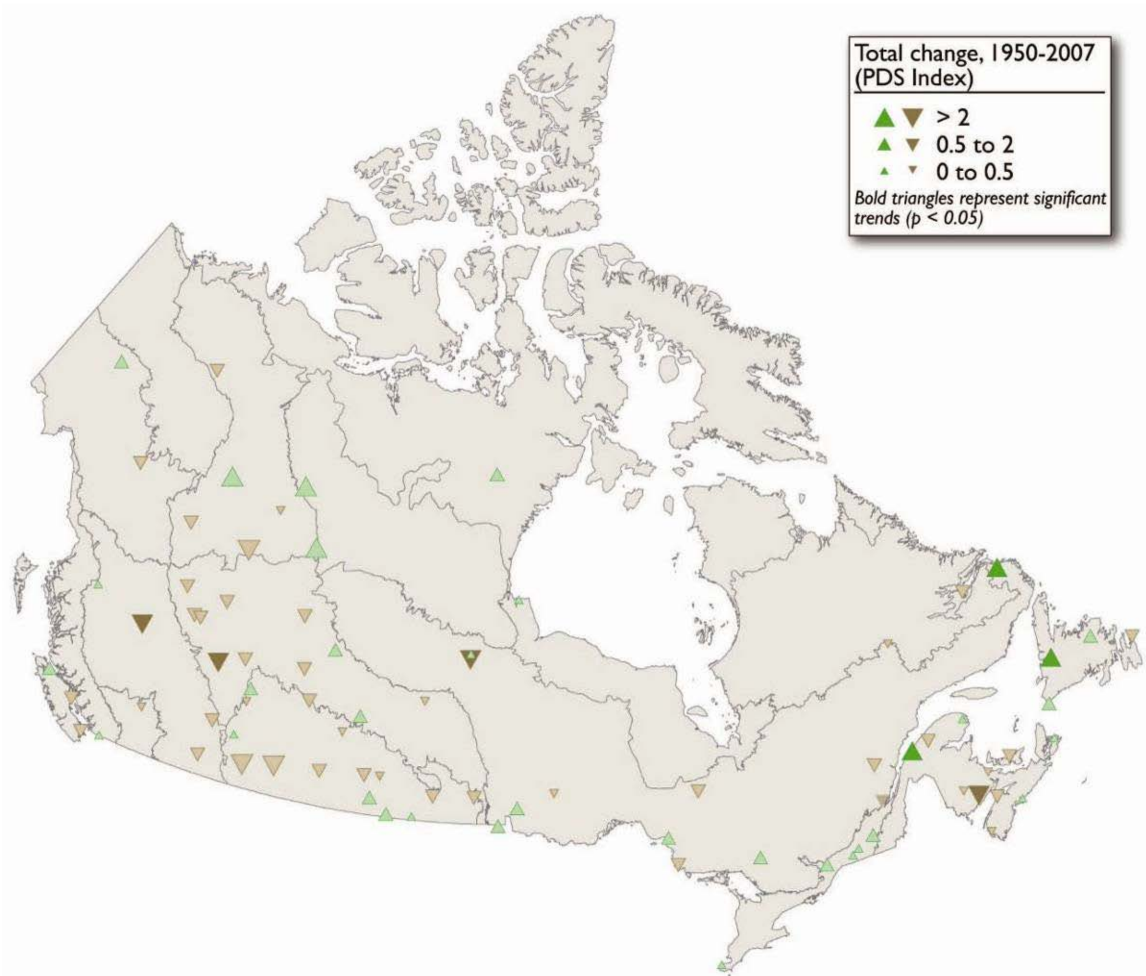

Figure 7. Change in the Palmer Drought Severity Index (PDSI) for summer (June- August), 1950-2007.

Snow and ice conditions

Interannual variability and trends in the duration of snow and ice cover are closely linked to air temperatures in the fall and spring periods. Analysis of trends in snow cover duration in the first and second halves of the snow year (defined from August to July) (Figure 8) are consistent with the fall and spring temperature trends shown in Figure 2 with little change in snow cover in the fall but widespread decreases (39% of stations) in spring snow cover over western and northern Canada in response to warmer spring temperatures. The significant trend to earlier snow melt 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). The maximum depth of snow cover also shows a general tendency to smaller values (Figure 9), but less significantly (19% of stations) and less spatially coherent than spring snow cover duration. Over southern Canada the decrease in maximum snow depths is being driven by less winter precipitation (Figure 4d) and a lower fraction of precipitation falling as snow from winter warming (Figure 2d and Figure 10). The decreases in maximum depth reported at some Arctic stations is difficult to explain as this region experienced increasing precipitation and an increase in the fraction of precipitation falling as snow from 1950 to 2007, also documented in Vincent and Mekis (2006), and climate models suggest that maximum snow accumulation will increase over northern high latitudes in response to global warming (Brown and Mote, 2009).

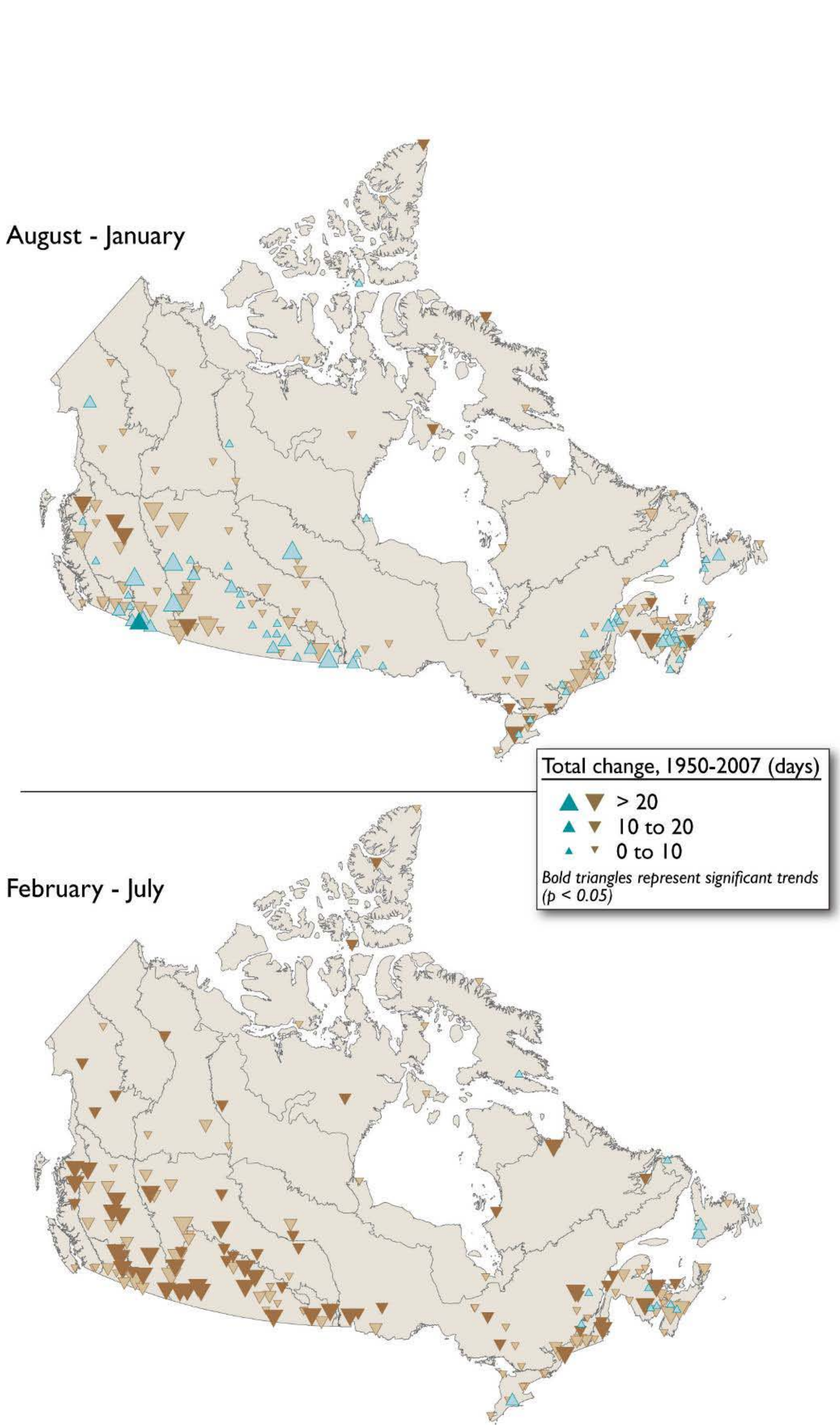

Figure 8. Change in the number of days with ≥ 2 cm of snow on the ground, 1950-2007, in a) the first half of the snow season (August to January) which indicates changes in the start date of snow cover, and b) in the second half of the snow season (February to July) which indicates changes in the end date of snow cover.

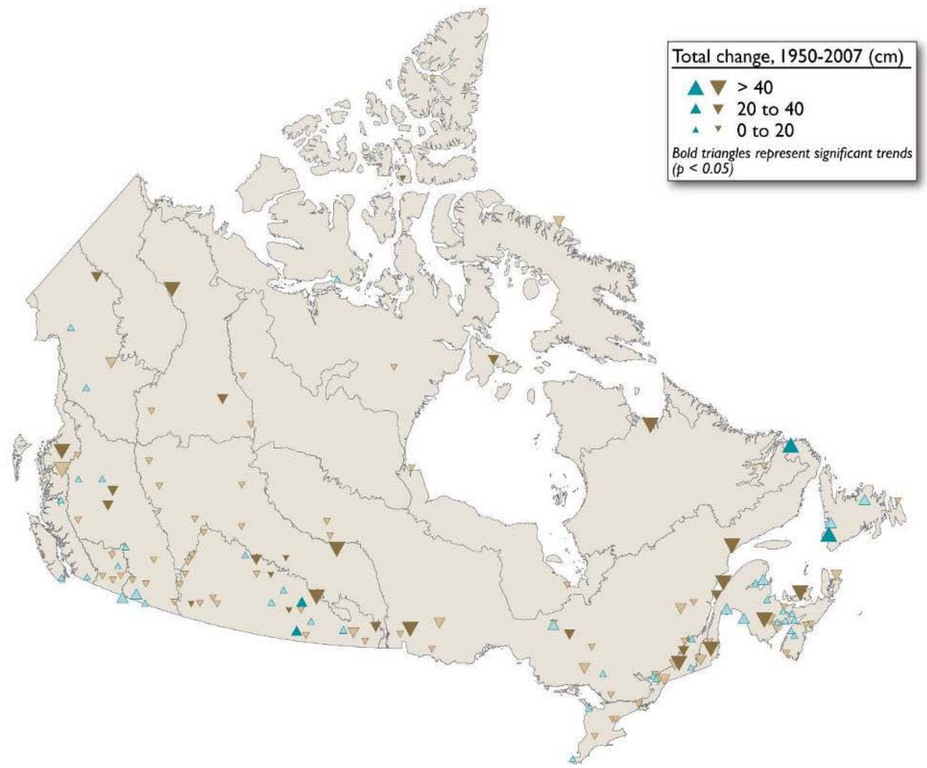

Figure 9. Change in the maximum annual snow depth, 1950-2007.

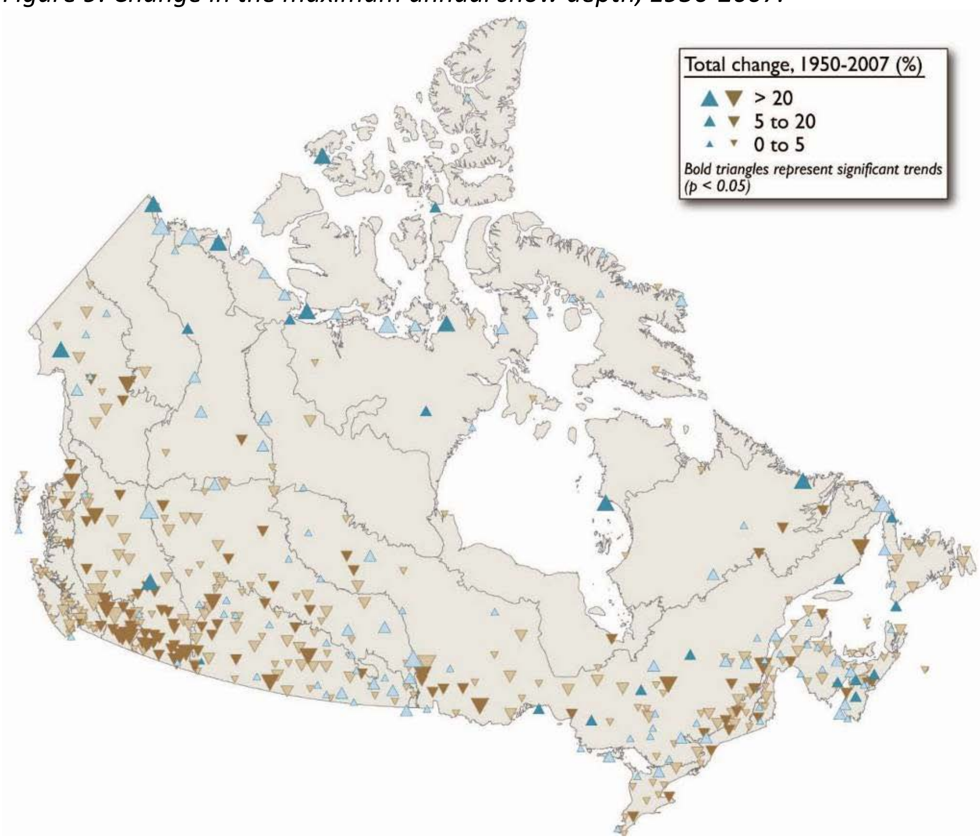

Figure 10. Absolute change in the ratio of snow to total precipitation in Canada, 1950-2007. Decreasing trends indicate a decrease in the proportion of precipitation falling as snow.

Analysis of river and lake ice freeze-up and break-up trends from the mid 1960s to the mid 1990s show contrasting seasonal responses with little change in freeze-up (with some evidence of earlier river ice formation over eastern Canada) but widespread trends for significantly earlier spring break-up (Zhang et al., 2001a; Duguay et al., 2006). These results are consistent with trends in fall and spring temperatures shown in Figure 2. A more recent analysis of trends in freeze-up and break-up at approximately 40 lake sites across Canada from 1970 to 2004 using in situ and satellite observations showed greater evidence of significantly later freeze-up at a number of lakes (Latifovic and Pouliot, 2007). The spatial pattern of trends in thaw date over the 1950 to 2005 period shows that sites with significantly earlier break-up tend to be located in western Canada (Figure 11) in agreement with the spatial pattern of climate stations showing significant spring warming (Figure 2a).

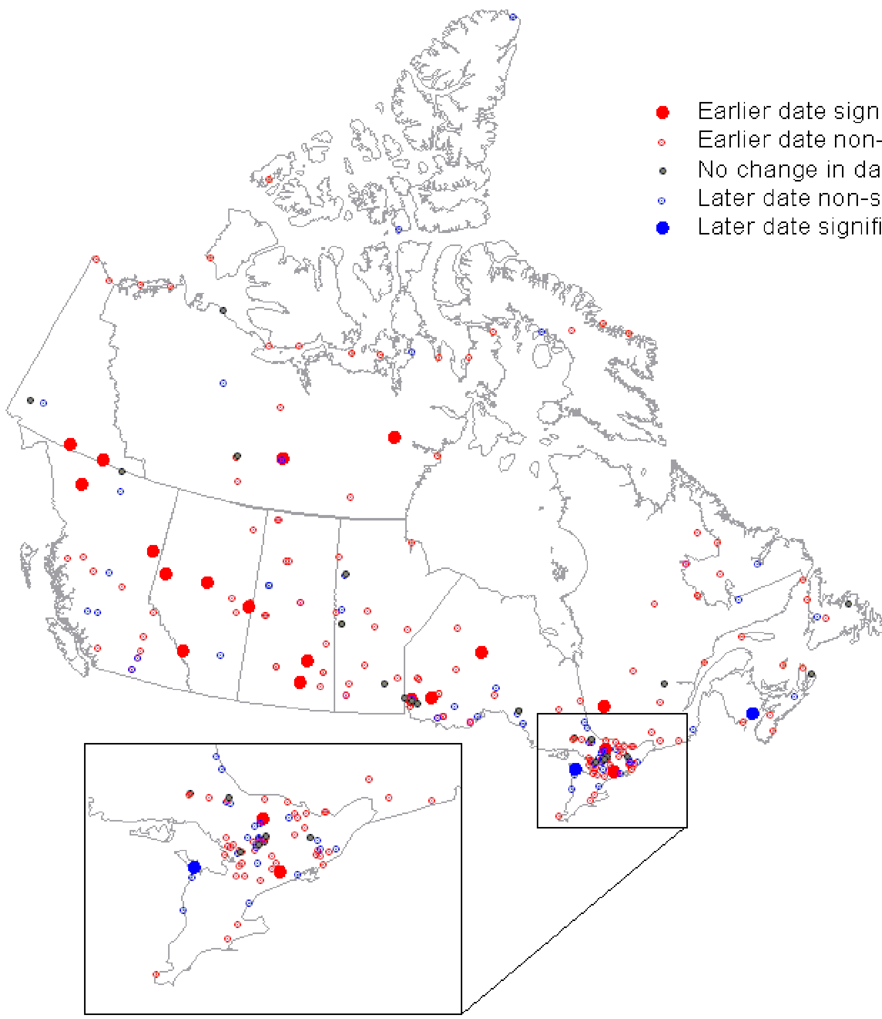

Figure 11. Trends in lake ice thaw date across Canada, 1950-2005.
Source: IceWatch (2008a)

Changes in hydrological regime

Analysis of streamflow trends during the second half of the 20th century (Zhang et al., 2001a) indicates a general decrease in annual mean streamflow during that period, with significant decreases detected in the southern part of the country. Monthly mean streamflow for most months also decreased, with the greatest decreases occurring in August and September. The exceptions are March and April, when significant increases in streamflow were observed. Significant increases were identified in lower percentiles of the daily streamflow frequency distribution over northern British Columbia and the Yukon. In southern Canada, significant decreases were observed in all percentiles of the daily streamflow distribution. Breakup of river ice and the ensuing spring freshet occur significantly earlier, especially in British Columbia consistent with the spring warming trends shown in Figure 2a.

Changes in the growing season

Statistically significant increases in the length of growing season have been observed mainly in the southwest (Figure 12). Some decreases in the growing season length were seen in the Prairies, but the decreases are not significant in general. The increase in the length of growing season is largely due to an earlier start of the growing season as a result of spring warming (Figure 13). In most regions of Canada, growing season has started earlier and many stations show significant earlier starts to the growing season. The longer growing season in combination with warmer temperatures during the growing season, has resulted in significant increases in growing degree days (Figure 14). There is also evidence of a reduction in the frequency of occurrence of frost days and killing frost days during the growing season (Qian et al., 2010).

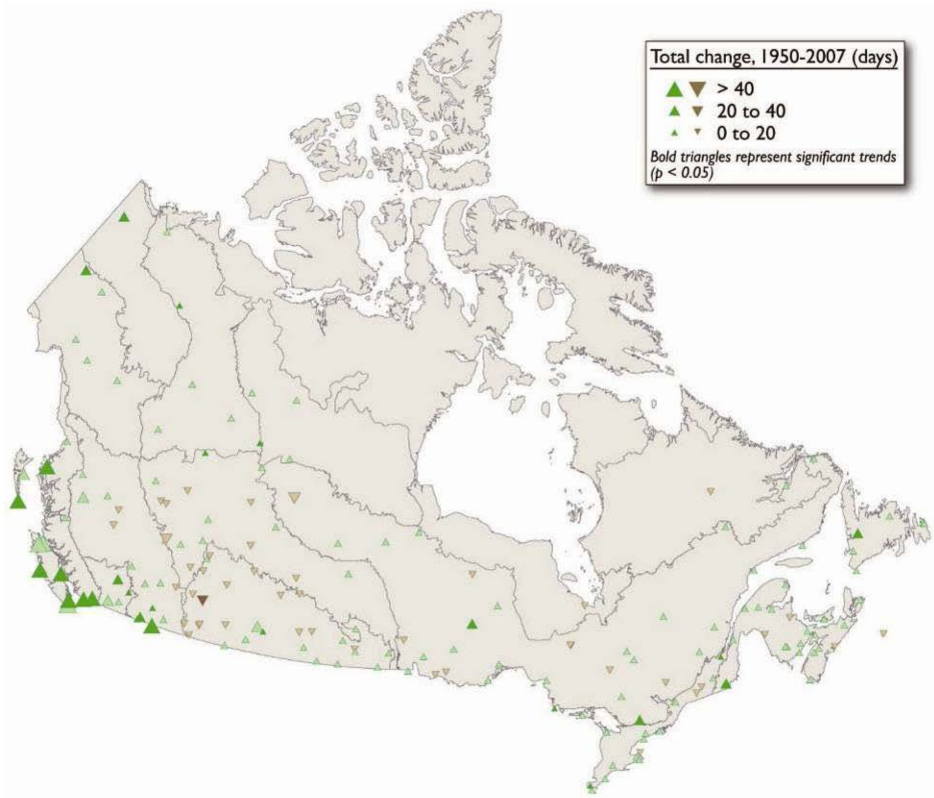

Figure 12. Change in the length of growing season, 1950-2007.

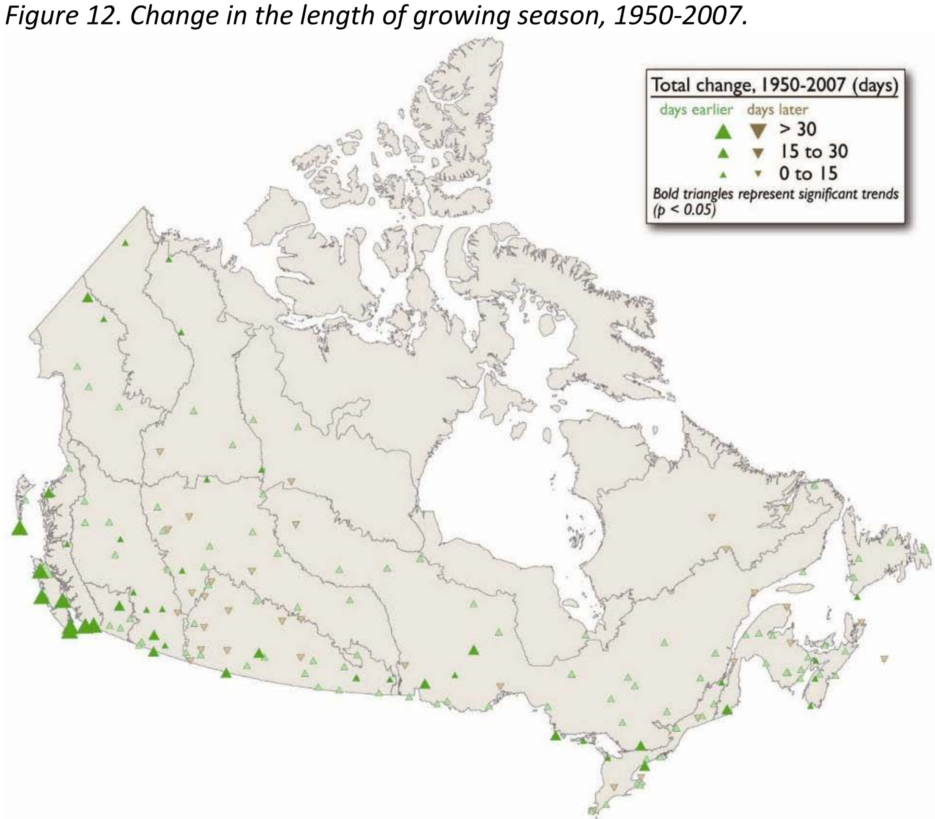

Figure 13. Change in the start date of the growing season in Canada, 1950-2007.

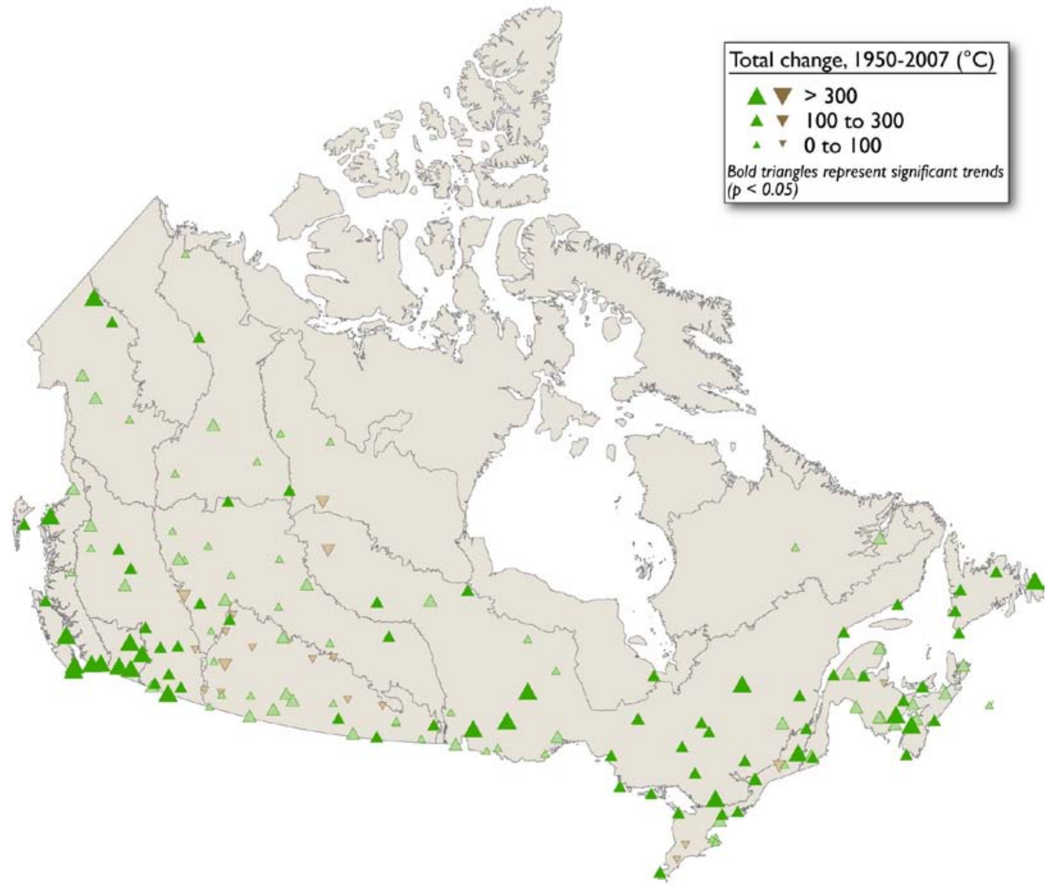

Figure 14. Change in the effective growing degree days (a measure of accumulated heat during the growing season), 1950-2007.

SUMMARY

Canada's climate has changed considerably since 1950: temperatures have increased over much of the country, and precipitation has also increased, especially over northern Canada. These are driving trends in other climate variables that are of significance to ecosystems, for example a shorter snow cover season, less winter snow accumulation, earlier melt of snow and ice in the spring, an earlier and longer growing season with fewer frost days, and decreasing potential for water availability. These changes are also associated with fundamental shifts in hydrologic regimes such as a decrease in the fraction of precipitation falling as snow over southern Canada, and earlier spring runoff. Studies have suggested that the observed warming trend in Canadian temperature and perhaps the increase in precipitation over northern Canada can be attributed to human emissions of greenhouse gases (Lemke et al., 2007; Min et al., 2008). These trends are also consistent with climate model projections over North America (Meehl et al., 2007) that indicate a warmer and wetter climate for many regions of Canada in the future. The implications of these changes on Canadian ecosystems are discussed in the Technical Ecozone+ Reports.

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