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An Assessment of Changes in Winter Cold and Warm Spells over Canada

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Abstract. The recent Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) indicated that observed 20th century changes in several climatic extremes are qualitatively consistent with those expected due to increased greenhouse gases. However, a lack of adequate data and analyses make conclusive evidence of changing extremes somewhat difficult, particularly, in a global sense. In Canada, extreme temperature events, especially those during winter, can have many adverse environmental and economic impacts. In light of the aforementioned IPCC report, the main focus of this analysis is to examine observed trends and variability in the frequency, duration, and intensity of winter (Jan–Feb–Mar) cold and warm spells over Canada during the second half of the 20th century.

Cold spell trends display substantial spatial variability across the country. From 1950–1998, western Canada has experienced decreases in the frequency, duration, and intensity of cold spells, while in the east, distinct increases in the frequency and duration have occurred. These increases are likely associated with more frequent occurrences of the positive phase of the North Atlantic Oscillation (NAO) during the last several decades. With regard to winter warm spells, significant increases in both the frequency and duration of these episodes were observed across most of Canada. One exception was found in the extreme northeastern regions, where warm spells are becoming shorter and less frequent. The results of this study are discussed within the context of climate warming expectations.

Key words: Canada, climate change, cold spell trend, exponential distribution, Kendall's tau, Poisson distribution, warm spell trend

1. Introduction

There is a general consensus among most climatologists that the advent of global warming will be accompanied by changes in the frequency and intensity of climatic extremes. Significant changes in these extremes will stress society's current adaptation to climate variability and consequently, their impacts should be discernible at an early stage. From this standpoint, detection of changes in extremes takes on added importance in the climate change debate. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001) recognizes the lack of adequate data and analyses to fully conclude that on a global basis, climatic extremes have changed during the 20th century. On regional scales, however, there is convincing evidence of changes in some extremes. Although the conclusions are somewhat mixed, TAR does state that specific temperature results appear to be robust. This includes observed decreases in the probability of extreme cold days and increases in the probability of extreme warm days over many regions of the globe (Karl *et al.*, 1999). As well, with increases in the concentration of greenhouse gases and other constituents, a number of Global Climate Models (GCMs) are producing climate scenarios with increased frequencies of extreme high temperature events, and decreases in extreme low temperature events for the end of the 21st century (Kharin and Zwiers, 2000). This has led TAR to conclude “the changes in extremes we have already observed are qualitatively consistent in a very general way with those changes in climate model simulations of future climate, indicating these changes in extremes would be likely to continue into the future”.

An important extreme temperature event involves the occurrences of hot and cold spells (i.e., consecutive days of extreme high/low temperatures). Over Canada, extreme cold events during winter occasionally persist for prolonged periods, creating health/safety hazards, and great inconveniences and disruptions in economic activities. Recent compilation of mortality data from Statistics Canada (1998) shows that there is an annual average loss of 103 lives due to excessive cold. Comparatively, excessive summer heat claims eight lives on average. Although perceived as beneficial, extreme winter warm events can also adversely affect environmental and economic activities including for example, winter transportation, flooding, and the skiing industry. In view of the recent IPCC report, the main objective of this study is to assess whether recent observed trends and variability in the frequency, duration, and intensity of winter (Jan–Feb–Mar) cold and warm spells over Canada are consistent with those expected in a warmer world.

2. Data and Methodology

Temperature data employed in this analysis consist of daily minimum and maximum values for 210 high quality (i.e., few missing values, minimal urban effects), relatively evenly distributed stations across Canada (see for example Figure 3a). For these data, homogeneity problems caused by station relocation and changes to instrumentation and observing practices have been addressed using a regression model technique (Vincent, 1998). Monthly adjustment factors were obtained for identified inhomogeneities and a database of homogenized monthly values was created (Vincent and Gullett, 1999). Additional refinement has included adjustment for daily temperatures based on linear interpolation of target values derived from the monthly factors (Vincent *et al.*, 2002).

Climatological observations prior to the 1950s are sparse in the northern regions (north of 60° N) of Canada. Therefore, the majority of trend analyses in the frequency, duration, and intensity of spells are confined to the 1950–1998 period. However, long-term climatological aspects in the frequency and duration of spells for selected stations over more southern regions of the country use the entire period of available data (1900–1998). Stations having more than 20% of their observations missing (for the period in question) are excluded from the computations. In general, missing observations were not confined to a particular period, but were distributed throughout the record. This ensures that there is no bias in the description of spells toward a particular period in time.

To define cold spells, the 20th percentile of the daily minimum temperature distributions (during the winter period) are determined for each station during the 1961–1990 climatological base period. Individual cold spells are then defined as those events in which the minimum temperatures remained below this threshold for at least three consecutive days. It is believed that a minimum of three days is required before significant effects of extreme winter temperatures are felt. With this definition, a spell lasting six days, for example, would still be considered as one six-day spell (as opposed to two three-day spells). Similarly, warm spells are defined as those events in which the winter daily maximum temperatures remained above the top 80th percentile for at least three consecutive days. Other percentile threshold definitions were also examined. For example, the stricter 10th percentile for minimum and 90th percentile for maximum temperature yielded too few spells for reliable linear trend analyses. In addition increasing the duration from three to five days did not significantly change the results.

The trend calculation for this investigation incorporates a statistical model that takes into account the spurious effects of the serial correlation. For this model, the noise in the data is represented by a 1st order auto-regression. Lag-one correlation is firstly removed from the time series. Subsequently, the non-parametric Kendall's tau (Sen, 1968) procedure is used to determine both the magnitude and the statistical significance of the trend. Since the Kendall estimate is less sensitive to the non-normality of the distributions, it is preferred over the least squares methodology. The current procedure guards against the effects of outliers and extreme values while fitting a trend line to the data. Further details about this procedure are found in Zhang *et al.* (2000). All trends are assessed for statistical significance at the 5% level.

3. Results

3.1. CLIMATOLOGY OF WINTER COLD SPELLS

To the authors' knowledge, no previous studies have addressed the occurrence of cold and warm temperature spells over Canada. As a result, this section attempts to obtain a better understanding of the climatological characteristics in winter spells over various regions of the country. Long-term climatologies in the frequency and duration of winter cold spells are examined for several, regionally varying stations over the country. These stations include Prince George, British Columbia, Fort Simpson, Northwest Territories, and Regina, Saskatchewan (all representative of western Canada); Welland and Ottawa, Ontario (central Canada); and St. Anthony, Newfoundland (eastern Canada). Note that the climatological values are based on the entire period of record for each of these stations. Figure 1 shows distributions in the frequency of cold spells at each of these stations. The Kolmogorov–Smirnov test (Wilks, 1995) reveals that the empirical distributions at the stations follow the Poisson distribution at the 1% level of significance (shown by solid lines). The mean number of spells and the 95% confidence band around the mean are also provided. On average, most locations experience just over two cold spells per year. The lowest average frequency is associated with the Great Lakes' station of Welland and may be attributable to more frequent incursions of warmer, maritime air masses from the southeast. Further analyses indicate that there is a 75% probability of getting two or more cold spells over western Canada. This number drops to 55% over the Great Lakes region, but rises to around 70% over eastern Canada (not shown).

Distributions of cold spell durations for the same set of stations are shown in Figure 2. The exponential distribution is often used to model lifetime or waiting time of climatological events (Rice, 1995) and appears to fit the duration data quite well. The average durations of the cold spells along with their 95% confidence bands are assessed from this fitted distribution. The average duration of spells is highest in the west, and decreases toward central and eastern regions of the country. For example, the mean duration of 6.5 days at Prince George is considerably longer than the mean duration of 3.7 days at St. Anthony. This is likely attributable to frequent outbreaks of Arctic air into western regions which often results in prolonged periods of very cold temperatures. Variability in the length of cold spells is also higher over western Canada. This agrees with the findings of Bonsal *et al.* (2001a) who determined highest winter temperature variability over this region of the country.

3.2. TRENDS AND VARIABILITY IN WINTER COLD AND WARM SPELLS

Due to the lack of adequate data north of the 60° N prior to the 1950s, trends in cold and warm spells are mainly examined only for the 1950–1998 period. Figure 3a shows that the frequency of winter cold spells has generally decreased over much of western Canada. Values range from one to two fewer spells with only a few significant values over British Columbia and Alberta. Consistent with these results, Bonsal *et al.* (2001b) found an upward trend in the values representing the 5th percentile of daily minimum winter temperatures over western Canada for the same period. Most of the western Arctic, including the high Arctic islands also show decreases in the number of winter cold spells (although not significant). On the other hand, large portions of eastern Canada display several statistically significant increases during this period, particularly along the east coast. Trends are near two spells over the 49-year period for most of this region. Over central Canada, there are small changes towards increasing numbers of cold spells. For the most part these trends are not significantly different from zero.

The frequency of winter warm spells (Figure 3b) shows increases throughout most of Canada. Several stations are statistically significant in the area extend-

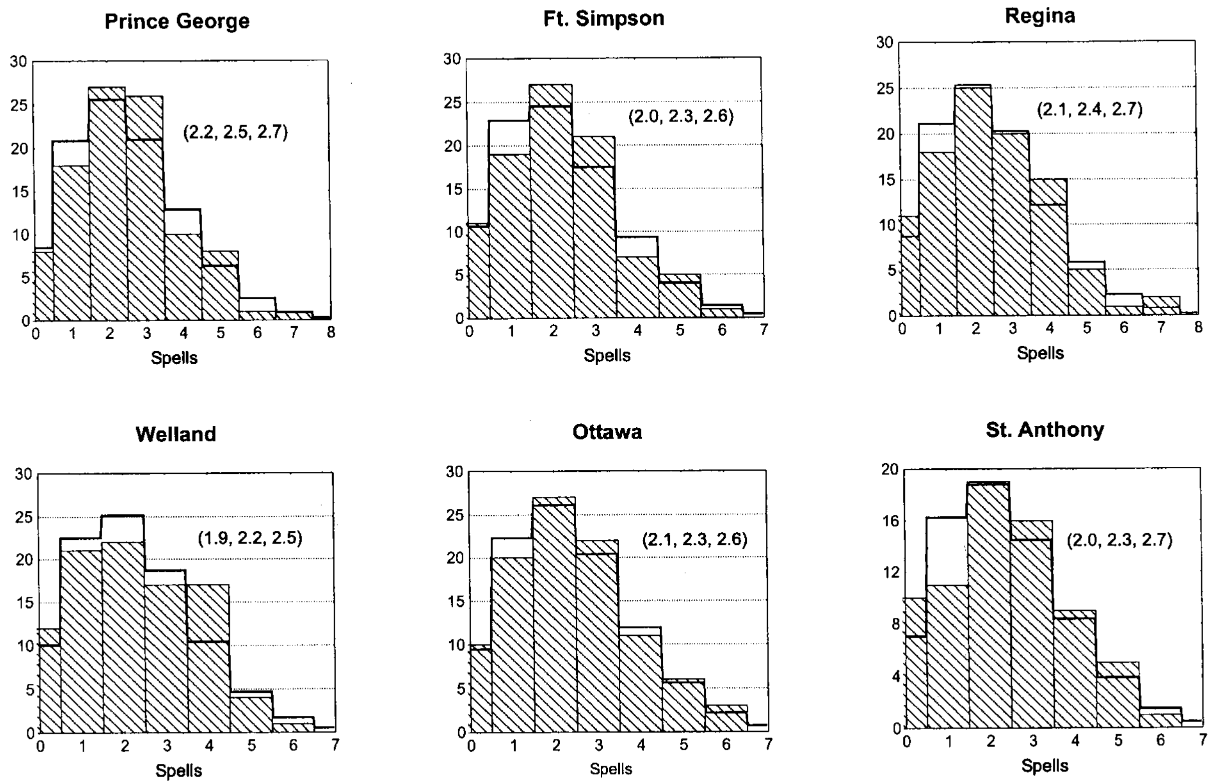

Figure 1. Distributions showing the frequency of winter cold spells at selected stations across Canada. Distributions are based on the entire period of record for each station. Solid lines represent the fitted Poisson distribution. The mean number of spells and the corresponding 95% confidence limits (as determined by the Poisson distribution) are shown in parentheses for each station.

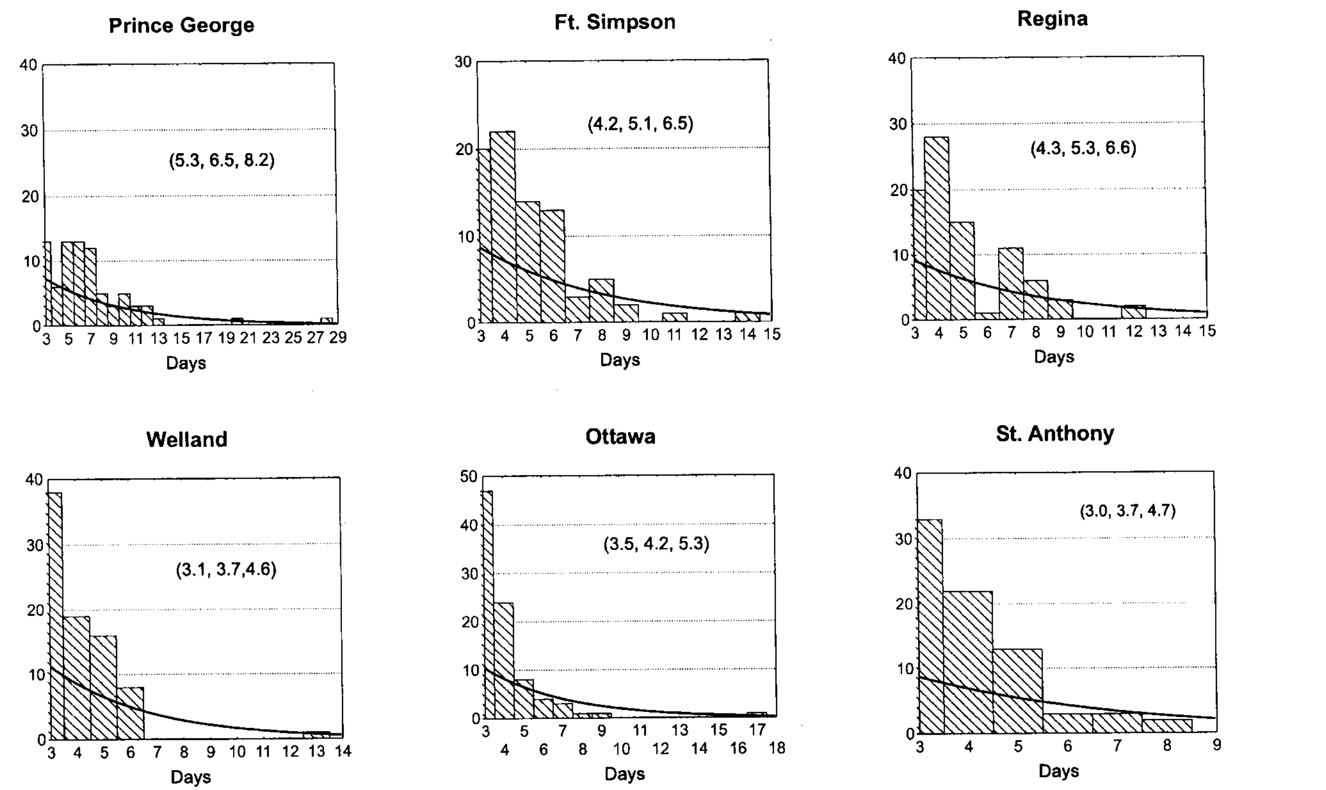

Figure 2. Same as Figure 1 except distributions showing the duration of winter cold spells. Solid lines represent the fitted exponential distribution.

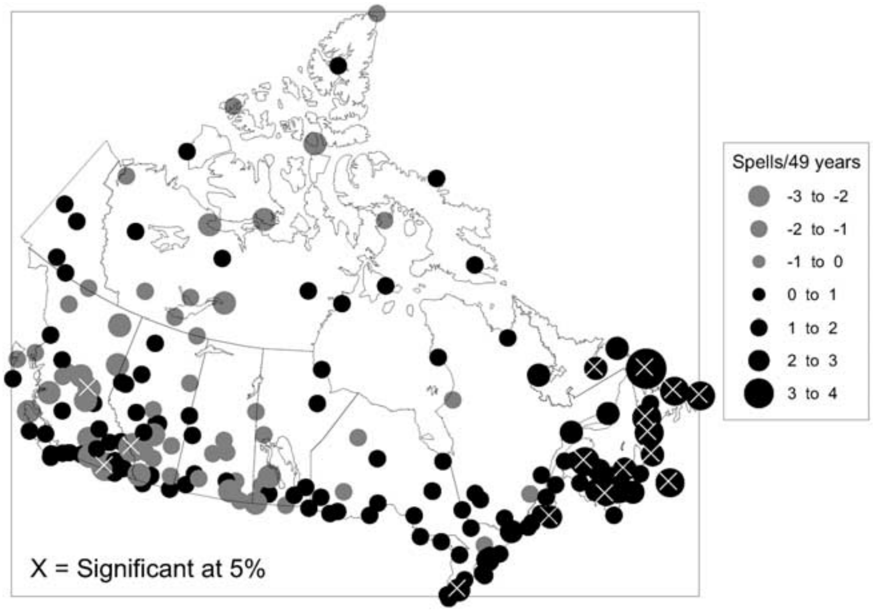

Figure 3a. Trends in the frequency of winter cold spells during the 1950–1998 period. Units are in number of spells/49 years. Stations with significant trends at the 5% level are denoted by X.

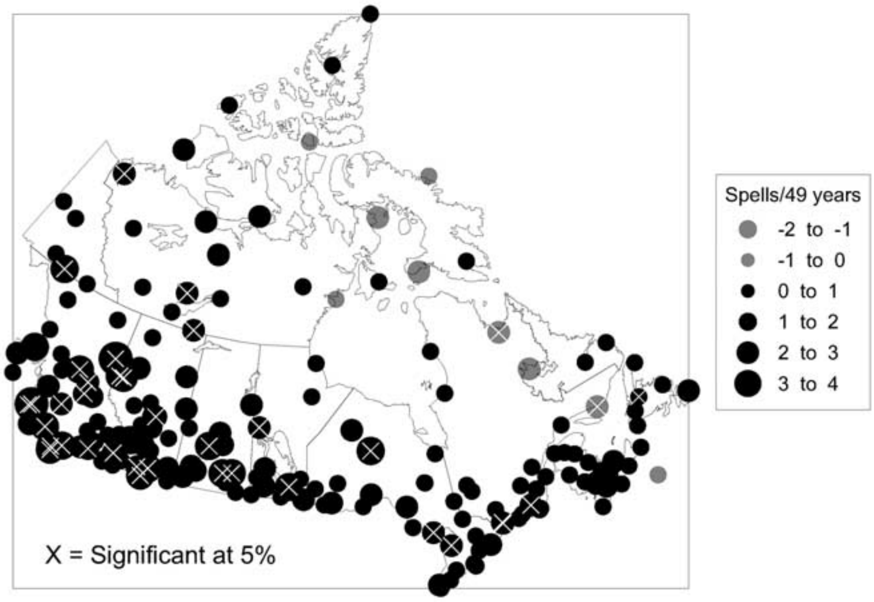

Figure 3b. Same as Figure 3a except for the frequency of winter warm spells.

ing from the Great Lakes to the Yukon and in particular, over southern British Columbia and western Prairie provinces. This is the same region where the winter cold spells have generally shown a decreasing trend. In eastern Canada, the increases are generally small and not significant. Arctic areas tend to display regional differences including increases in the frequency of spells over the west, and decreases over the east. In summary, trends in the frequency of winter cold and warm spells over Canada show considerable spatial variability over the country. Greatest overall changes have occurred over western areas including significant increases in the numbers of warm spells, and decreases in cold spells (although generally not significant). Central Canada tends to show smaller changes with general increases to both warm and cold spells. Eastern regions are also associated with increases to both types of spells; however, they are only statistically significant in terms of cold spells.

Another important component in the assessment of winter cold and warm spells involves changes in their duration. Figure 4a shows somewhat mixed results in the cold spell duration trends. In general, they are getting shorter in western Canada and the western Arctic, however, in the east, there is a tendency towards longer cold spells (particularly along the east coast). The majority of trends in Figure 4a are not significant. Winter warm spells (Figure 4b) are increasing in duration over the majority of the country with the largest changes in British Columbia. One exception is in Newfoundland-Labrador and Baffin Island where the duration of warm spells has decreased. The patterns in Figures 4a and 4b both closely resemble the trends in the frequency of cold and warm spells shown in Figures 3a and 3b.

An attempt is also made to determine if any significant changes to the intensity of cold and warm spells has occurred. For this analysis, intensity is defined as the average daily minimum/maximum temperature during all days contained within a spell(s) for the winter in question. The spatial distribution of cold spell intensity trends (Figure 5a) shows varying results over the country. The most dominant feature includes the large increases (5 to 7 °C) for many stations over the Northwest Territories, Alberta and British Columbia. Due to the high degree of variability inherent in cold spell intensities over this region, only a few stations show significant trends at the 5% level. Nonetheless, the large positive trend values do suggest that the intensity of cold spells is decreasing (i.e., average temperature within the spells is increasing) during the last 50 years. In the east, mixed and generally insignificant trends are observed. There may be a tendency for slight decreases in average temperatures signifying increases in cold spell intensity. With regard to warm spell intensity, Figure 5b shows significant increases of 2 to 3 °C over southern British Columbia. Temperatures have also risen 1 to 2 °C in the southern parts of Alberta, Saskatchewan and Manitoba. The rest of the country generally displays insignificant trends.

The preceding trends provide limited information regarding the interannual variability associated with cold and warm spells. Insight into this variability is provided in Figures 6a and 6b, which show time series of the frequency of winter

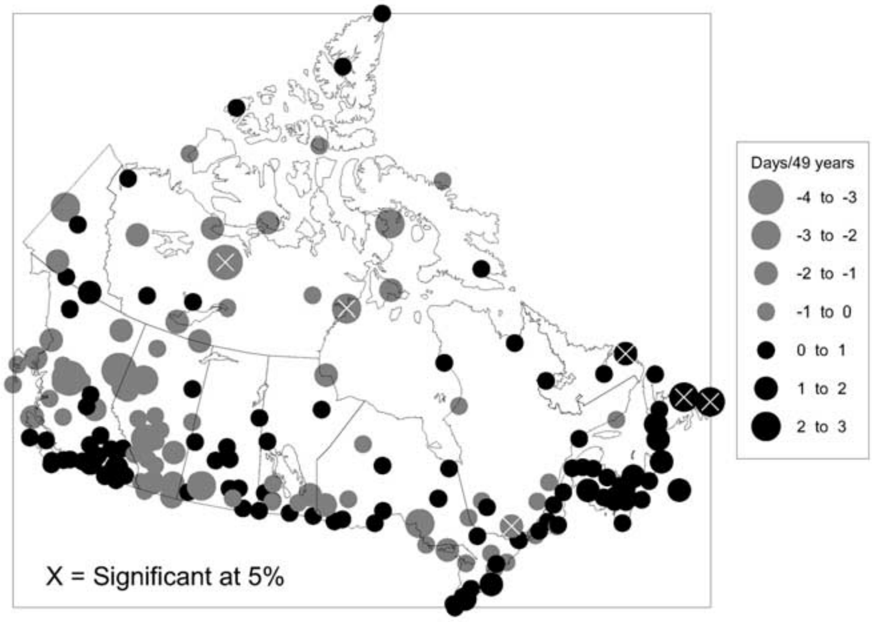

Figure 4a. Same as Figure 3a except for the duration of winter cold spells. Units are in days/49 years.

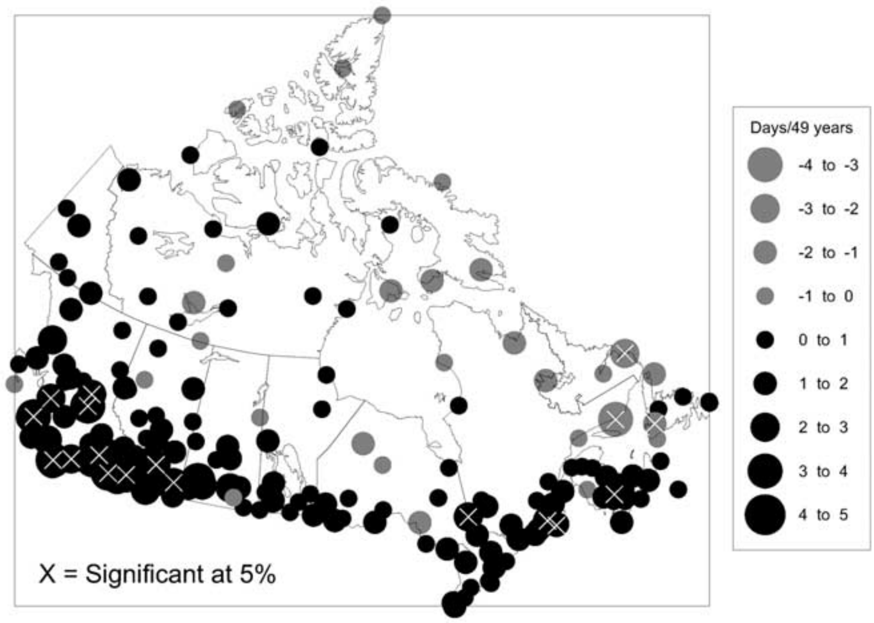

Figure 4b. Same as Figure 4a except for the duration of winter warm spells.

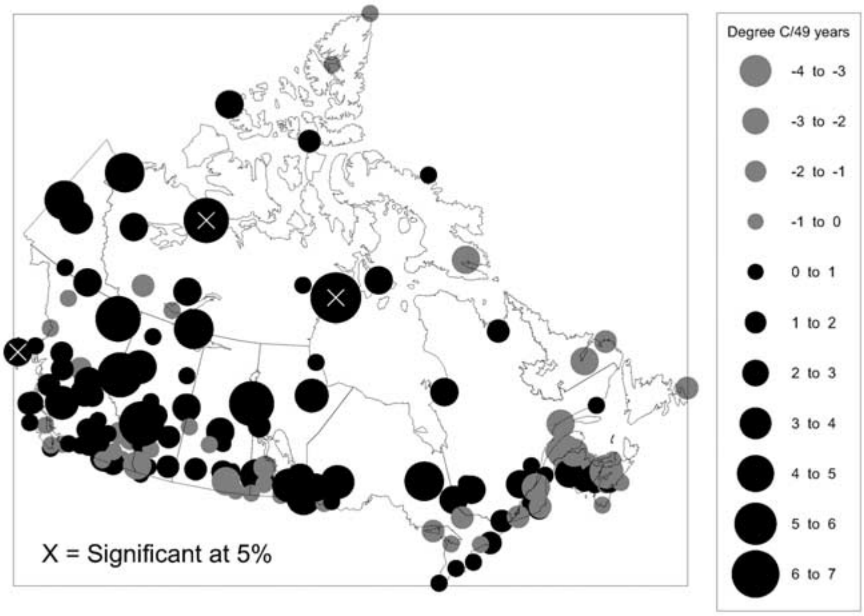

Figure 5a. Same as Figure 3a except for the intensity of winter cold spells. Units are in °C/49 years.

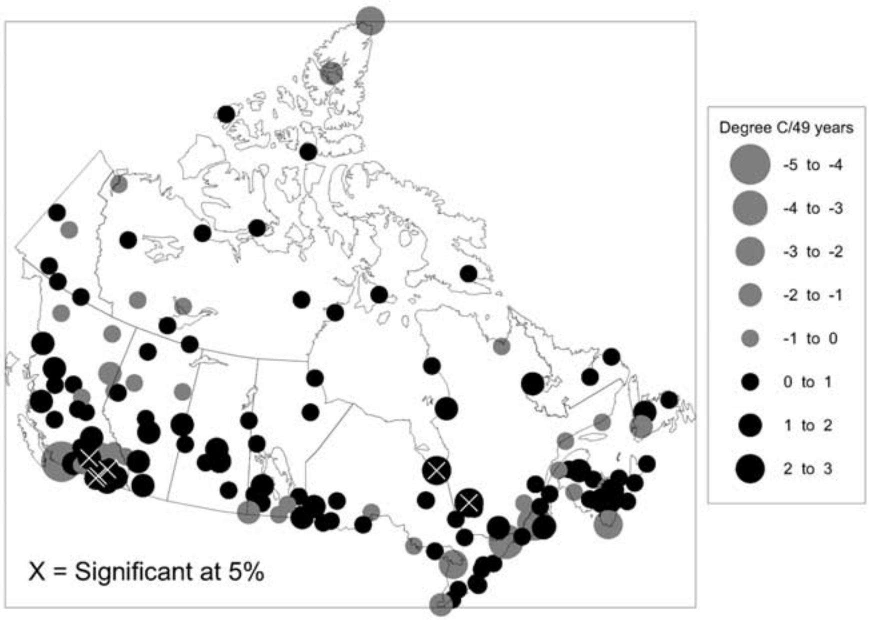

Figure 5b. Same as Figure 5a except for the intensity of winter warm spells.

cold and warm spells for the same six stations presented in Section 3.1. Series include the full period of record available at each station. A five-point Gaussian is also shown. For cold spells, Figure 6a shows that along with a strong component of interannual and in some cases, interdecadal variability, there is a discernible downward trend in the number of cold spells throughout the 20th century at western Canadian stations. In central Canada, there appears to be little change in the frequency while numbers are increasing at the east coast station of St. Anthony. This is exemplified by a sharp increase during the1970–1998 period (shown by the solid line). It is worth noting that the larger number of cold spells from 1900–1930 and from 1970 onwards, and the relative dearth of spells in the intervening period, bears resemblance to the 20th century time series of the North Atlantic Oscillation (NAO) (Bonsal *et al.*, 2001a). Concomitant with the decrease in western Canadian cold spells, the number of winter warm spells shows a noticeable increase in the same area (Figure 6b). Central Canada also displays a steady increase in the frequency of winter warm spells, particularly from around 1980 onward. In the east, there has been a slight decrease in the number of warm spells over the 20th century. At St. Anthony, an average of two warm spells in the early 1900s has decreased to about one spell by the end of the century.

4. Summary and Discussion

This investigation examines recent trends and variations in the frequency, duration, and intensity of winter cold and warm spells over Canada. Results reveal regional differences in terms of the magnitude and in some cases, the sign of the trends over various regions of the country. In terms of cold spells (Figures 3a, 4a, 5a, 6a), western regions of the country are generally associated with decreases to both the frequency and duration. Figure 5a also suggests that the intensity of cold spells has been decreasing over this region. Many of the aforementioned cold spell trends are generally not significant for the 1950–1998 period. However, trends for the longer 1900–1998 period (not shown) tend to display more stations with significant decreases in cold spell frequencies over western areas. Eastern Canada exhibits opposite cold spell results. In particular, both the frequency and duration of these spells has significantly increased during the last half century, but the intensities of these spells have not significantly changed. Central regions of the country display mixed, generally insignificant cold spell trends. Winter warm spells (Figures 3b, 4b, 5b, 6b) tend to show more spatially coherent results. The majority of the country is associated with significant increases to the frequency and duration of these spells (especially over the west). One exception, however, is over extreme northeastern portions of the country where warm spell frequencies and durations have actually decreased (see the St. Anthony time series in Figure 6b). There is no discernible spatially coherent pattern in warm spell intensity trends over the country.

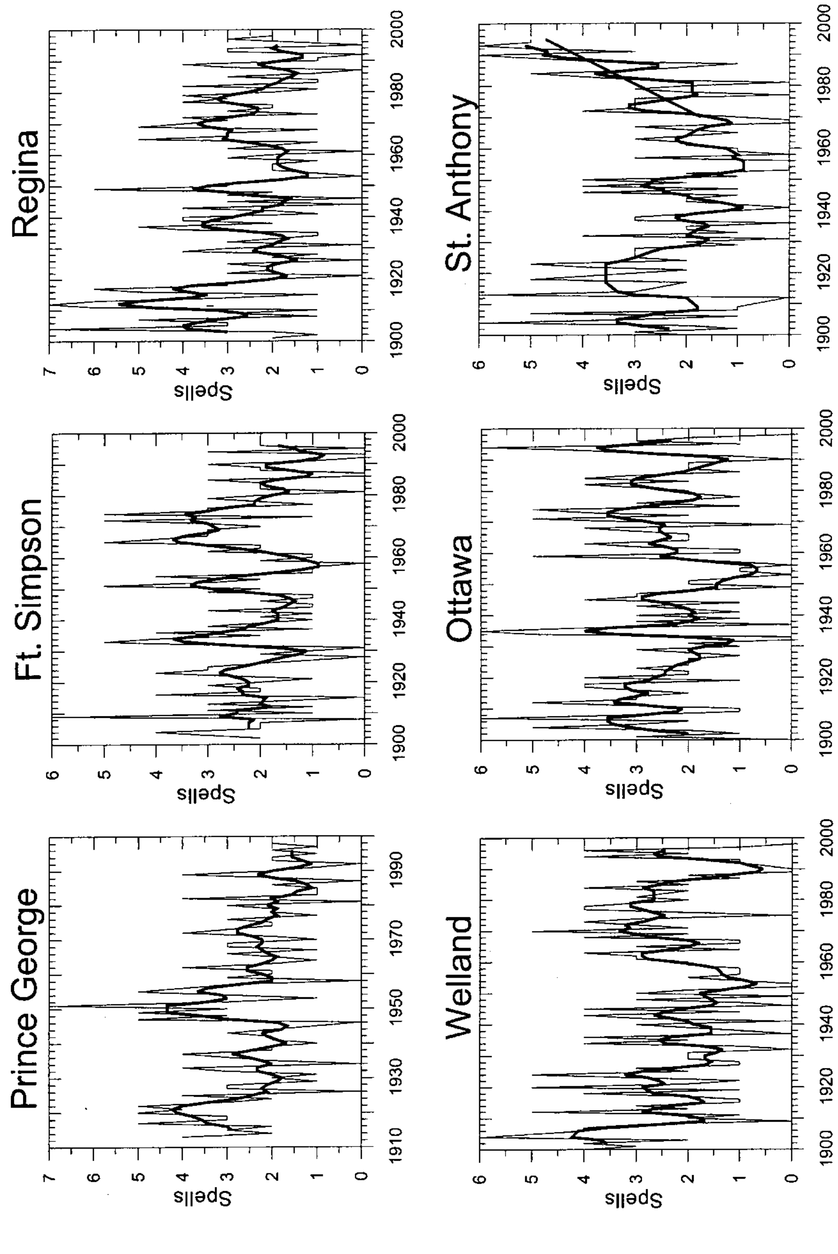

Figure 6a. Time series in the frequency of winter cold spells over available periods of record for selected stations across Canada. Five-point Gaussian filter is shown by heavy line.

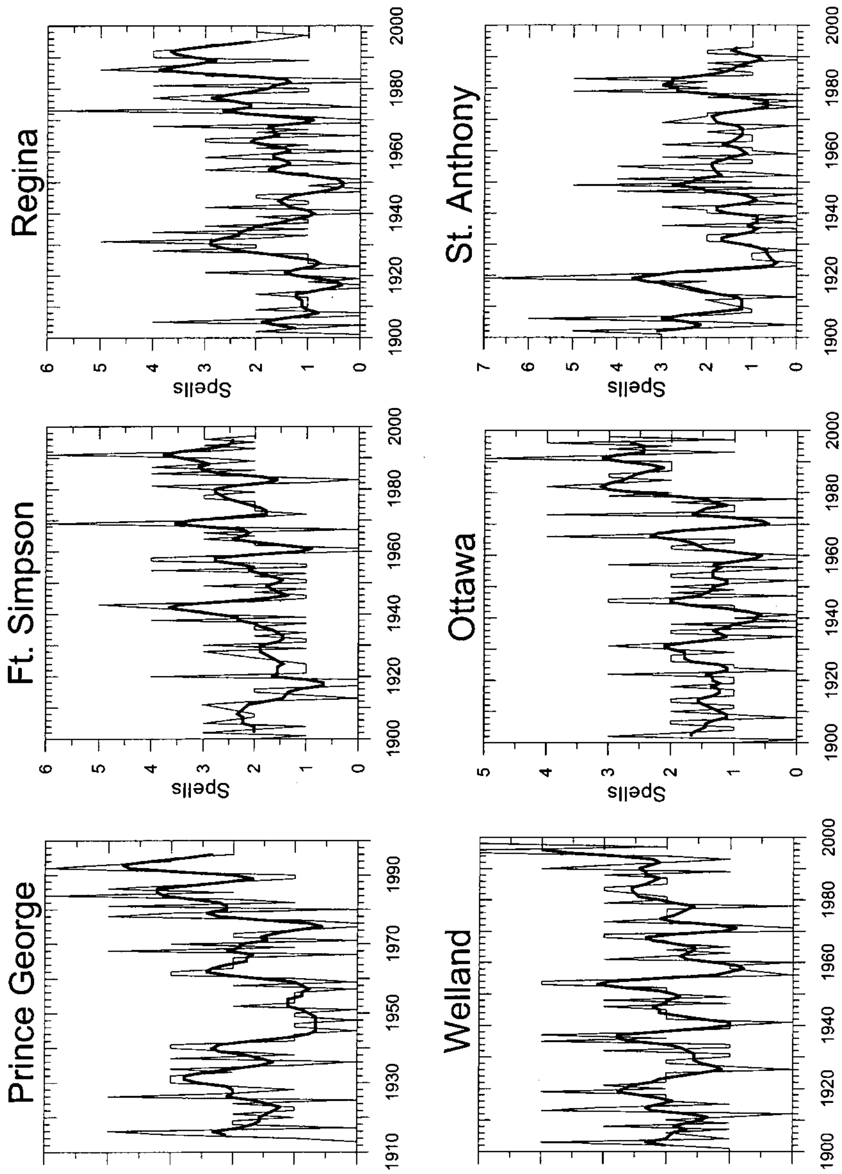

Figure 6b. Same as Figure 6a except for the frequency of winter warm spells.

The spatial aspects of winter cold and warm spell trends observed in this study agree with those found by Zhang *et al.* (2000) and Bonsal *et al.* (2001b) who have examined 20th century trends in seasonal and daily temperatures over Canada. In particular, during winter, both minimum and maximum temperatures significantly increased in western Canada, and decreased in eastern Canada from 1950–1998. Central portions of the country experienced smaller insignificant trends (see Figures 10 and 11 in Zhang *et al.* (2000)). The cold and warm spell results in this study show these same spatial characteristics. The exact causes associated with these observed trends are not clear and require further investigation. It appears that some trends are consistent with expectations of greenhouse gas induced warming while others are not. The decreases in the frequencies, durations, and intensities of cold spells over western portions of the country, and the increases in the number and length of warm spells over most of Canada are what would be expected in a warmer world. However, the increases in cold spell frequency and duration over the east appear inconsistent with these expectations. The most recent ensembles of multi-coupled model experiments (IPCC 2001) project significant warming in annual mean temperature over northern land areas during the 21st century. Although the models do not suggest cooling over eastern Canada, they do reveal somewhat smaller temperature increases in the north Atlantic sector (as compared to the rest of the Northern Hemisphere land regions).

The observed large degree of spatial variability in the winter cold spells over Canada also strongly suggests the influence of variations in low frequency atmospheric and oceanic circulation modes. For example, the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) (Mantua *et al.*, 1997), and the NAO have been shown to prominently affect winter climate over Canada (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997; Bonsal *et al.*, 2001a), and these phenomena likely have a significant role in determining variations in winter spells. The increases in the frequency of cold spells over eastern Canadian station of St. Anthony (Figure 6a) closely resembles decadal-scale shifts in winter NAO variability during the 20th century indicating some degree of influence on winter spells in this region. At present, the effects of global warming on these large-scale oscillations remain somewhat uncertain. In fact, TAR points to a lack of agreement amongst various climate models concerning the frequency and the structure of the naturally occurring modes of climate variability with increased greenhouses gases.

Recent studies have suggested that rises in greenhouse gas concentrations may act to cool the stratosphere and strengthen the polar vortex. Thompson and Wallace (2000) determined that fluctuations in the strength of this vortex during winter are strongly linked to sea level pressure variability in the Northern Hemisphere, and in particular, a positive phase of the NAO. Furthermore, a modelling study has indicated that the trends toward the positive NAO phase are associated with the progressive warming of the tropical Pacific and Indian oceans (which has been linked to global warming) (Hoerling *et al.*, 2001). Since the positive NAO is strongly associated with winter cooling over eastern Canada, the trends toward increased frequencies and durations of cold spells may indeed be a regional response to global warming.

In conclusion, analyses of extreme winter temperatures over Canada appear to conform to the TAR of the IPCC (2001) statement regarding observed trends in extreme temperature events. In particular, there have been reductions in the frequency, duration, and intensity of winter cold spells in western Canada, and increases in the frequency and duration of warm spells over the majority of Canada during the latter half of the 20th century. In addition, the eastern Canada trends toward increased frequencies and durations of cold spells may be a regional manifestation of rising temperatures in tropical regions of the globe. It is realized that further research into the attribution of these observations as well as, a similar study of spells during the summer season is required in order to develop a full appreciation of the 20th century changes to persistent temperature events. A preliminary examination of the summer season indicates small increases in the number of warm spells throughout most of Canada; however, significant values are observed for only a few stations in the western Arctic. The knowledge obtained here, along with ongoing advances in GCM and Regional Climate Model (RCM) modeling exercises will provide better insight into future changes in these events.

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