Spatial and Temporal Characteristics of Heavy Precipitation Events over Canada

XUEBIN ZHANG, W. D. HOGG, AND ÉVA MEKIS

Climate Research Branch, Meteorological Service of Canada, Environment Canada,
Downsview, Ontario, Canada

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ABSTRACT

Spatial and temporal characteristics of heavy precipitation events over Canada (excluding the high Arctic) are examined for the period 1900–98. In southern Canada, about 71% of total precipitation comes from rainfall events. In northern Canada, more than 50% of total precipitation comes from snowfall events. Heavy rainfall and snowfall events are thus defined for each season and station separately by identifying a threshold value that is exceeded by an average of three events per year. Annual and seasonal time series of heavy event frequency are then obtained by counting the number of exceedances per year. Characteristics of the intensity of heavy precipitation events are investigated examining the 90th percentiles of daily precipitation, the annual maximum daily value, and the 20-yr return values. It was found that decadal variability is the dominant feature in both the frequency and the intensity of extreme precipitation events over the country. For the country as a whole, there appear to be no identifiable trends in extreme precipitation (either frequency or intensity) during the last century. The observed increase in precipitation totals in the twentieth century was mainly due to increase in the number of small to moderate events.

Stations with coherent temporal variability in the frequency of heavy precipitation events are grouped by cluster analysis and examined on a regional basis. Results show stations belonging to the same group are generally located in a continuous region, indicating that the temporal distribution of the number of events is spatially coherent. It is also found that heavy snowfall events are more spatially coherent than heavy rainfall events. Indices representing temporal variations of regional heavy precipitation display strong interdecadal variability with limited evidence of long-term trends. They vary markedly depending on the precipitation type, season, and region. Spring heavy rainfall events over eastern Canada have shown an increasing trend superimposed on the strong decadal variability. However, heavy rainfall events in other seasons/regions are generally not associated with any trends or decadal variability. The number of heavy snowfall events in southern Canada shows an upward trend from the beginning of the twentieth century until the late 1950s to 1970s, followed by a downward trend to the present. In the last 50 yr, heavy snowfall events in northern Canada have been increasing with marked decadal variation.

The majority of stations have a significant positive correlation between the total amount of snowfall contributed by heavy events versus that contributed from nonheavy events. The relationship is strongest over western Canada. On the other hand, relatively few (<20%) stations had a significant correlation between total rainfall in heavy events and nonheavy events. These results suggest that the amount of precipitation falling in heavy and nonheavy events increases or decreases coherently for snow, but not for rain.

1. Introduction

The prospect of global change resulting from anthropogenic causes has stimulated a variety of research focused on predicting future climate and its effect on the earth. One of the most important aspects of these studies is to characterize possible changes in climate extremes (e.g., floods, droughts, high winds, etc.) since these events have the strongest impact on society. It has been documented that even a small change in the mean condition can cause a large change in extreme statistics (Katz and Brown 1992). Consequently, the degree to which climate change affects society will more likely depend on changes in climate variability and, particularly, in the intensity and frequency of climate extremes. In addition, the observed trends and variability in extreme events may also be used as indicators to monitor climate change.

Modeling results have indicated increases in extreme precipitation in a warmer climate. Using equilibrium climate change simulations conducted at the Canadian Centre for Climate Modeling and Analysis (CCCma), Zwiers and Kharin (1998) showed that with a CO_2 doubling, precipitation extremes will increase over most of the globe. For North America, extreme precipitation that occurs on average every 20 yr in present climate, will occur every 10 yr in a warmer world. In Canada, the 2

Corresponding author address: Dr. Xuebin Zhang, Climate Research Branch, Meteorological Service of Canada, 4905 Dufferin St., Downsview, ON M3H5T4, Canada.
E-mail: Xuebin.Zhang@ec.gc.ca

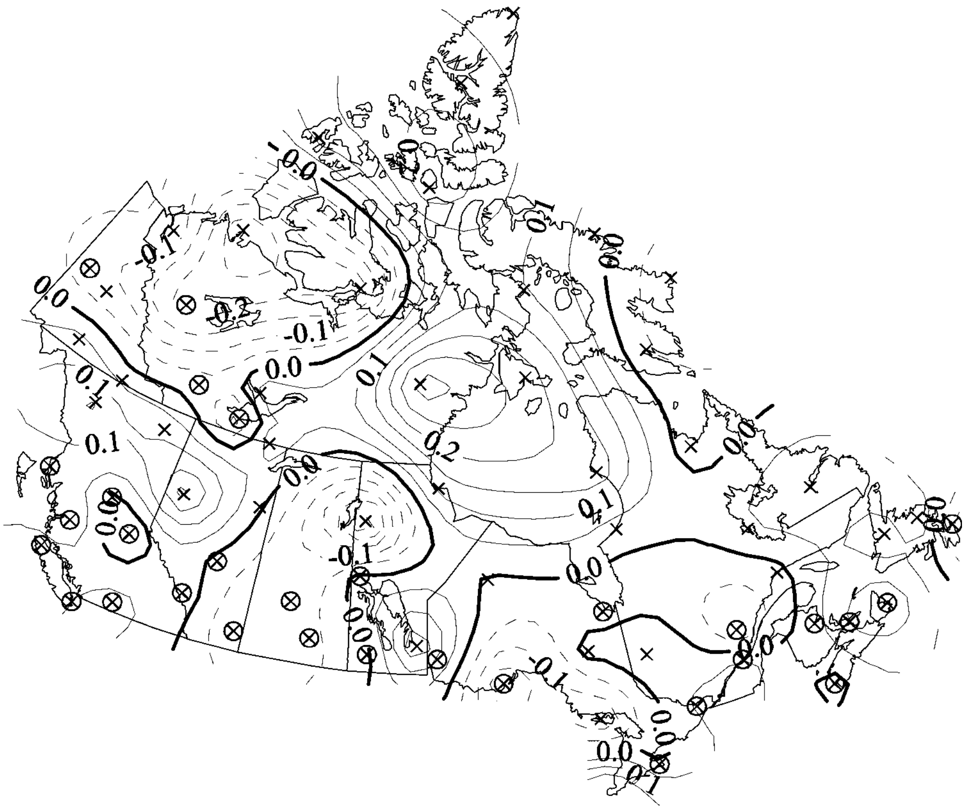

FIG. 1. Trend (1940–95) in the fraction of annual precipitation falling in the largest 10% of daily events (from Mekis and Hogg 1999). Stations that commenced data collection after 1940 and prior to 1910 are marked with black crosses and circled crosses, respectively. Unit is % year^{-1} of the annual total.

× CO_2 20-yr return values are increased by an average of approximately 14% as compared to present values. These results generally agree with other GCM studies (e.g., Cubash et al. 1995). Zwiers and Kharin (1998) speculated that the increase in extreme precipitation is likely a reflection of the increase in global temperature (and hence atmospheric moisture) thus resulting in an intensification of the hydrologic cycle.

Observational studies have also suggested evidence of changes in climate extremes. For example, Karl et al. (1996) reported that both the proportion of the United States with a much greater than normal number of wet days, and the fraction of annual rainfall occurring in extreme events have tended to increase. These precipitation changes were considered as a possible regional manifestation of global climate change.

Analyses of observed extreme precipitation events over Canada are limited. The studies mainly concentrated on evaluating inhomogeneities and sampling errors of annual extremes in daily rainfall (Hogg 1991; Hogg 1992). Cycles and trends in those extremes were also identified for selected stations across the country (Hogg 1995). The results showed that annual extremes in daily rainfall exhibited significant interdecadal variability with little evidence of a long-term trend. A recent study by Kunkel et al. (1999) examined the trends in a Canadian extreme precipitation index for the period 1951–93. No long-term trend was identified in the analysis.

Examining only one extreme precipitation index for all of Canada, or extreme precipitation events at individual stations, does not provide sufficient characterization of twentieth century extreme precipitation over the country. This is illustrated in Figs. 1 and 2, which show trends in the fraction of annual precipitation occurring in the largest 10% of daily events with measurable precipitation as derived from 68 adjusted Canadian stations (Mekis and Hogg 1999). Over a large portion of the country, there has been a tendency toward an increase in the fraction of annual precipitation falling in those large events over the last 46 yr (Fig. 1). However, when the average fraction of annual precipitation in those events for the 30 stations with data from 1910 to 1995 are compared with the remaining 38 stations, which commenced data collection after 1940 (Figs. 2 and 3), it is clearly evident that the upward trend since 1940 was dominated by the 38 short record stations. The majority of these stations are clustered in northern Canada. As a result, it appears that long-term variations in large precipitation events can vary dramatically by region and time period and one index is not sufficient

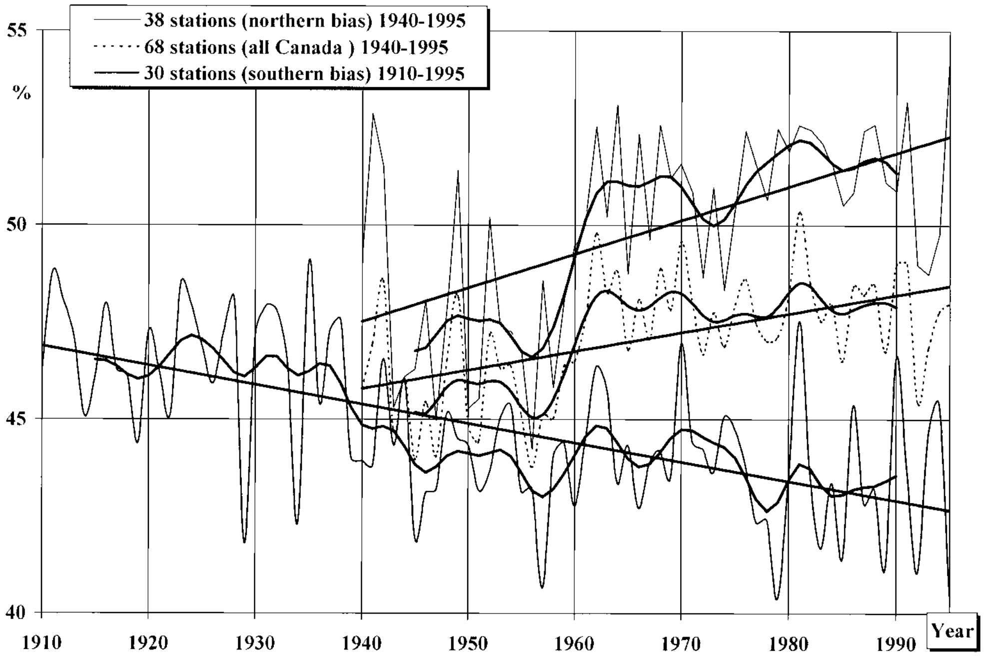

FIG. 2. Time series of fraction of annual precipitation falling in the largest 10% of events. Locations of stations are as marked in Fig. 1.

to represent these temporal variations for the entire country.

The occurrence of extreme precipitation often exhibits many spatial inhomogeneities. Individual station time series of extreme events are thus, generally unsuitable for trend analysis. However, given the large-scale nature of climate change, it is reasonable to assume that changes or trends in extreme precipitation are more spatially consistent than extreme precipitation itself. It should therefore be possible to describe observed changes in extreme precipitation conditions using regionalized indices over homogeneous regions. Due to the annual cycle, annual maximum rainfall events may all occur in a single season or may be drawn from different types of events in different seasons. Limiting an analysis to annual maxima may only reflect climate change for a particular season. This would not be sufficient for the identification of a climate change signal or for assessing the possible impacts of climate change. It is more rigorous and useful to analyze seasonal extreme precipitation separately, including snowfall events (which have important impacts on Canada). The main purposes of this study are therefore 1) to document twentieth century variations of extreme precipitation over Canada, 2) to provide a framework for mapping extreme events into regional indices, and 3) to characterize the spatial and temporal variations of extreme snowfall and rainfall events over the country based on these regionalized indices. The data and the methodology are described in the next section. A national summary of several precipitation variables including temporal variations in both the frequency and intensity of heavy events is provided in section 3. These variations are also compared to changes in other areas of the daily precipitation distribution as assessed by trends in various percentiles of daily precipitation. Section 4 focuses on more detailed analyses of heavy precipitation events at a regional scale. A discussion with concluding remarks follows in section 5.

2. Data and methods

a. Data

This study utilizes the adjusted daily rainfall and snowfall amounts described in Mekis and Hogg (1999). All known inhomogeneities in the station data due to changes in the measurement programs were carefully minimized. Wind undercatch, wetting loss, evaporation, trace events, and varying snow densities were also considered in the adjustment procedure. As a result, this is the most homogeneous long-term dataset currently available for Canadian daily precipitation. Inhomogeneity in the number of trace events caused by changes in observation procedure is difficult to correct, trace events are therefore not considered in this study. There was a slight change in the thresholds of measurable precipitation, from 0.01 in. (0.25 mm) for an MSC gauge to 0.2 mm for the new Type-B gauge in late 1970s. This change may have introduced small inhomogeneity in the number of precipitation days, but its effect on the result of the subsequent analysis should be very minimal: this is supported by the fact that almost all of the observed increase in Canadian precipitation amount and

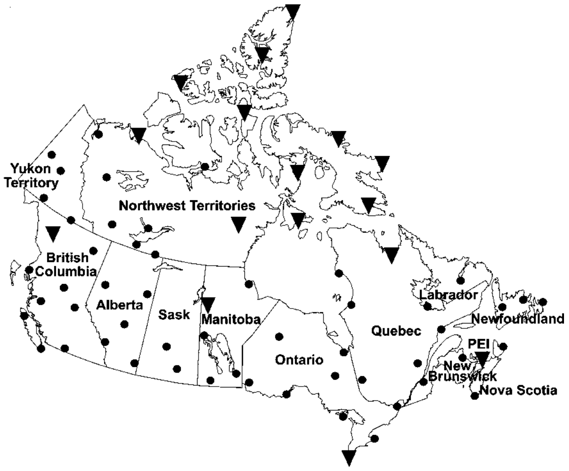

FIG. 3. Locations of the 68 stations used in this study. The 51 stations with more than 50 yr of data and the 17 stations with less than 50 yr of data are marked with black dots and triangles, respectively.

daily frequency occurred prior to the introduction of the new gauge (Mekis and Hogg 1999). The construction of national and regional indices of extreme events is performed on 51 evenly distributed stations with more than 50 yr of data. All of these stations are located south of 70°N (Fig. 3) with the majority having data from 1900 to 1998. To examine the spatial distribution of trends across all of Canada, an additional 17 stations with less than 50 yr of data are also used.

An extreme precipitation event is normally defined as a daily amount exceeding a certain threshold. Karl et al. (1996) used a threshold of 2 in. (50.8 mm) to define extreme precipitation events for the United States. Mekis and Hogg (1999) noted that this threshold was not suitable for Canadian precipitation since the mean intensity of extreme events decreases rapidly in latitudes above 50°N. Furthermore, for large portions of the country, a 50-mm event is exceptionally rare. They also determined that due to substantial variations in heavy precipitation across the country, the same fixed threshold is not appropriate for every station; they therefore considered the largest 10% of daily precipitation events as extremes. For the purpose of this study, extreme events are defined for each season and station separately by identifying a threshold that is exceeded by an average of three events per year. This definition ensures that only extreme events are included and also results in at least one event during most years. It identifies approximately the largest 10% of measurable rainfall or snowfall events for most stations during summer or winter. Since some stations do not have data for the entire 1900–98 period, thresholds based on daily values from 1961 to 1990 (during which all stations have good data coverage) are defined. Extreme events for different stations are thus comparable. To avoid possible confusion between our definition of extremes and those that include only annual maximum events, events identified by our definition will be termed as heavy events in the remainder of the paper. Seasons analyzed include: December–February for winter, March–May for spring, June–August for summer, and September–November for autumn. Over most of the country, rainfall is uncommon in winter and snowfall in summer. Summer heavy snowfall and winter heavy rainfall are therefore excluded from the analysis. Time series of the number of exceedances, the number of heavy events per year are generated for each station and season.

b. Methods

To document long-term variations of the frequency of heavy precipitation, heavy event indices are computed separately for precipitation, rainfall, and snowfall. Annual and seasonal heavy events are first determined for each station and each year, and then averaged to derive national and regional time series of indices representing the frequency of heavy events. National averages for other variables (e.g., magnitudes of heavy events, percentiles of daily precipitation, annual maximum daily precipitation, numbers of days with measurable precipitation, etc.) are computed based on ''normalized'' values. These are obtained by dividing by their corresponding 1961–90 mean value.

The magnitudes of extreme events (the 90th percentiles, maximum, and 20-yr return values of annual daily precipitation, rainfall, and snowfall) are also examined. These values are important to society because engineers often use them to derive design values for a wide range of safe and cost-effective structures. In addition, observed 20-yr return values can be compared with projections of future changes based on GCM simulations (Zwiers and Kharin 1998). In this study, 20-yr return values are computed using a procedure described by Zwiers and Kharin (1998). Generalized extreme value (GEV) distributions are fitted to annual maximum daily precipitation, rainfall, and snowfall using the method of L moments (Hosking 1990). To assess long-term variations, the probability distributions are fitted for 20-yr moving windows, and 20-yr return values are obtained by inverting the relevant distributions. The values are also normalized based on the 1971–90 climatology to compute a national average.

Spatial coherence in the variability of frequency of heavy events is characterized through classification into several homogeneous groups according to temporal variations in the number of the events. The spatial consistency of the stations belonging to the same group is then examined. Cluster analysis has long been recognized as an effective statistical tool in grouping stations into climatologically homogeneous regions based upon given meteorological parameters. Gong and Richman (1995) compared various clustering algorithms used in climatological studies. They found that nonhierarchical methods generally outperformed hierarchical ones. Therefore, this study incorporates the nonhierarchical

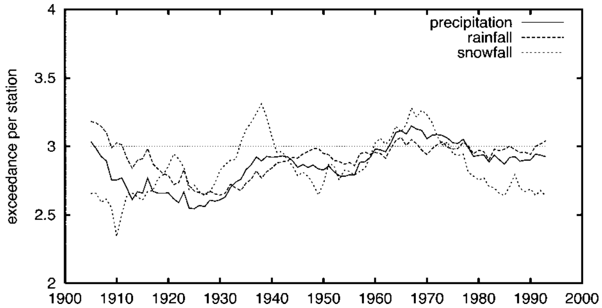

FIG. 4. The 11-yr moving averages of annual time series of average number of heavy events per location over Canada south of 70°N.

K-means clustering method based on the algorithm of Hartigag and Wong (1979). The K-means procedure determines definitions and memberships for a predefined number of groups so that total variance within each cluster is minimized. In particular, this method minimizes the Euclidean distance between the vector of number of heavy events for a station and the mean vector of number of heavy events of all stations within that cluster. Thus, stations are clustered according to similarities in their fluctuations in the number of heavy precipitation events.

Problems inherent to the various cluster analysis methods include the lack of measures to infer statistical significance, as well as the inability to determine the optimal number of clusters. This study classifies all stations into two to six groups and subjectively determines the number of clusters according to spatial consistency. After clustering the stations, several geographical regions are defined and the average number of heavy snowfall/rainfall events for each region calculated. These values are used as regional heavy snowfall or rainfall indices. Temporal variations of heavy events across the country are then characterized based upon these regional indices.

Characteristics of spatial patterns in Canadian heavy precipitation are further identified by computing linear trends in the ratio of precipitation falling in heavy events for every station. The relationship between precipitation falling in heavy events and nonheavy events is also examined by computing the correlations between these two variables.

Linear trends, their statistical significance, and their 95% confidence intervals are computed for various indices using a Kendall's tau-based nonparametric procedure described in Zhang et al. (2000). The statistical significance of correlations is evaluated by the F test. Significance in trends and correlations are assessed at the 5% level.

3. National summary

a. Frequencies of heavy events

Figure 4 displays the average number of heavy events per station for annual precipitation, rainfall, and snowfall over Canada (south of 70°N). Monotonically increasing or decreasing trends are absent in the annual series indicating no evidence of any significant long-term changes to the number of heavy precipitation events during the twentieth century. However, the indices do vary considerably from decade to decade. For example, the rainfall index was low during 1915–50 as compared to other periods. The number of heavy snowfall events was high from 1930 to 1940 and 1965 to 1975, and has shown a steady decrease since the 1970s. The total precipitation index shows more similarity to that of heavy rainfall events, indicating that annual heavy precipitation events are mainly influenced by rainfall events in Canada (high Arctic excluded).

Seasonal indices for the number of daily heavy rainfall and snowfall events are displayed in Fig. 5. The only statistically significant upward trend is associated with the number of heavy snowfall events during autumn. As with the annual series, Fig. 5 also suggests that decadal variability is a predominant feature in the seasonal indices. In particular, it appears that from the mid-1970s to approximately 1993, the number of spring heavy rainfall events was consistently higher than in any other period. Summer heavy rainfall events were generally higher early in the century, and lowest during the 1930s when much of western North America experienced severe summer droughts. Since 1950, there has been relatively no change in the number of these summer events. For heavy snowfall, there were gener-

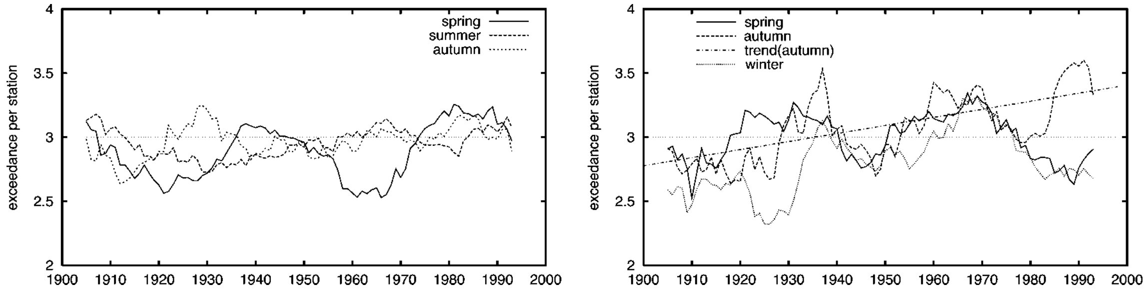

FIG. 5. Same as in Fig. 4 but for seasonal values with rainfall in left panel and snowfall in right panel. A significant increasing linear trend in autumn snowfall events is represented by a dash–dot line.

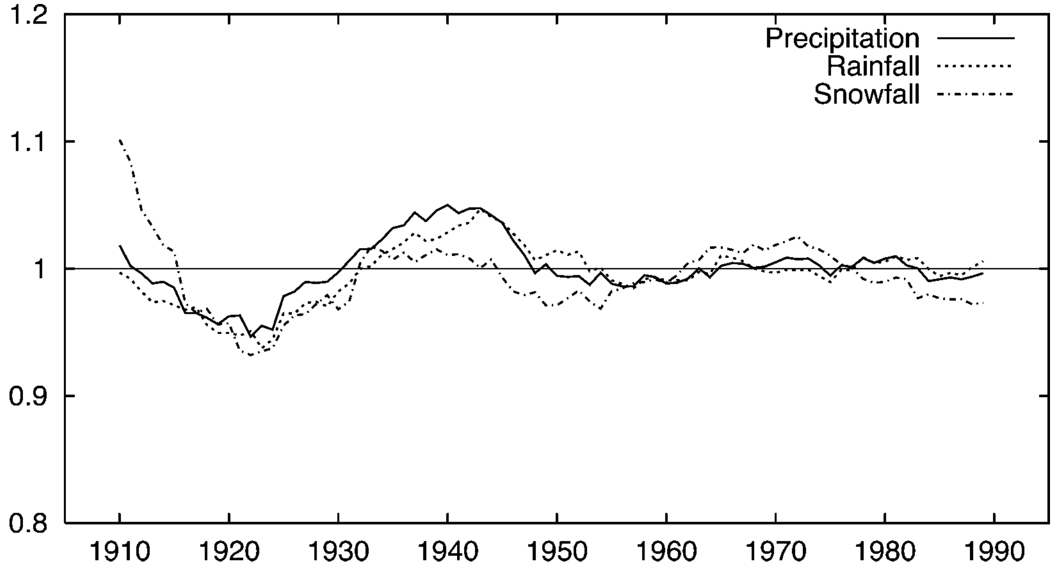

FIG. 6. Nationally averaged 20-yr return values (relative to the values for 1971–90) of annual maximum daily precipitation, rainfall, and snowfall. The 20-yr return values are first estimated using 20-yr running windows for every station, and then normalized by the values estimated for the period 1971–90. Values are plotted in the center of the 20-yr window.

ally fewer events after the mid-1970s during both spring and winter. This may also be related to the aforementioned changes in global circulation during the 1970s. Heavy snowfall indices for autumn showed a significant upward trend; however, strong decadal variations were also apparent.

b. Magnitudes of heavy events

Temporal variations in the normalized magnitudes (represented by the 90th percentiles, the annual maxima, and the 20-yr return values) of daily precipitation, rainfall and snowfall also exhibited strong decadal variation. For example, Fig. 6 shows the national averaged time series of normalized 20-yr return values. The series shows higher values in the early part of the twentieth century, during the 1940s, and to a lesser degree during the 1970s. Lower values occurred in the 1920s and 1950s. These variations are similar to those of heavy event indices (Fig. 4).

These results are similar to previous Canadian studies such as Hogg (1991) and Kunkel et al. (1999). They are also consistent with Canadian streamflow trends (Zhang et al. 2001), which showed no significant trends in annual maximum daily mean flow over southern Canada during the last half of the twentieth century. It therefore appears that at this point in history, increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada. The discrepancy between these findings and those projected by GCMs (e.g., Zwiers and Kharin 1998) may be due to the current stage of global warming. The observed 1°C warming trend over Canada (Zhang et al. 2000) during the twentieth century may be indicative of the early stages of the atmospheric response to increased greenhouse gases forcing and as a result, changes in extreme precipitation may not yet be detectable. In fact, an ensemble of transient climate simulations revealed that changes in 20-yr return values of annual maximum daily precipitation over Canada were small given the globally averaged screen temperature increase of 1.8°C associated with CO_2 doubling (Kharin and Zwiers 2000). However, the 20-yr return values showed much larger changes under $3 \times CO_2$ simulations when globally averaged temperature increased by 3.8°C. As well, observed warming in Canada to date, has been concentrated in winter and spring, seasons not expected to contribute to increases in extreme rainfall events, at least.

c. Percentiles of daily precipitation

In a recent investigation, Zhang et al. (2000) showed, with additional station data, an increase in total precipitation over southern Canada during 1920–70 and over northern Canada during the last 50 yr. As shown previously, heavy precipitation was not associated with significant trend. Therefore, it was decided to examine trends and variations in other areas of the daily precipitation (including rainfall and snowfall) distribution to determine the portion of distribution responsible for the increase in total precipitation. For every station, gamma distributions are fitted for daily precipitation, rainfall, and snowfall on an annual basis. Trends in nationally averaged normalized values of various percentiles (ob-

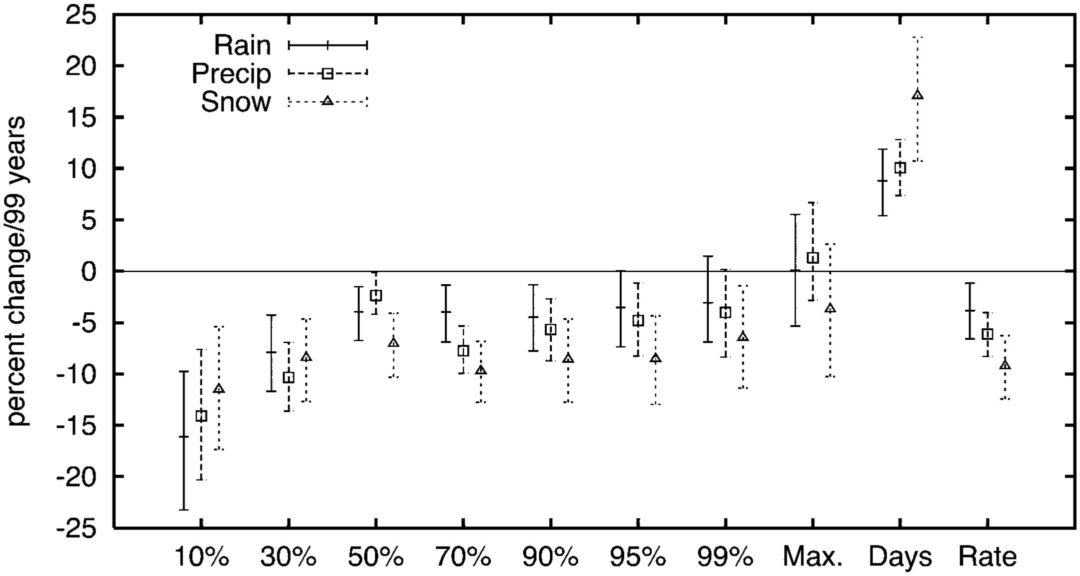

FIG. 7. Trends in nationally averaged normalized percentiles of annual daily precipitation. Units are percent change per 99 yr. The 95% confidence intervals are provided. Trends in the annual maximum values of precipitation, number of days with precipitation, and average precipitation rate are also shown. A trend is statistically significant at the 5% level if its 95% confidence interval does not cross the zero line.

tained from the gamma distributions), of the number of days with measurable precipitation, and of the rates of precipitation (average precipitation during days with measurable precipitation) were examined for each precipitation type.

Figure 7 presents trends in the variables along with their 95% confidence intervals. The most dramatic feature involves the significant increase in the number of days with precipitation (both rain and snow) during the twentieth century. This is associated with a significant decrease to the average rate of precipitation over the country. The majority of percentiles show negative trends with the larger decreases (in terms of percentage) in lower percentiles. Note that the higher percentiles show little trend and there are no significant changes in the annual maximum values. We see upward trends in the number of days and downward trends in the value defining the lower percentiles when the shape of the probability distribution of daily precipitation shifts toward more events in its left-hand side. Figure 7 indicates that the number of smaller rainfall events increased more than that of larger events, and the frequency of heaviest events did not increase at all. It therefore appears that the observed increase in precipitation during the past century is not due to increases in heavy precipitation, but rather to increases in the number of days with smaller precipitation. It should be mentioned that the increase in the number of days with precipitation mainly occurred during 1920–70, prior to the introduction of the new gauge, indicating that the increase in the number of wet days is not likely caused by change in the threshold of measurable precipitation.

In summary, the preceding has clearly shown that decadal-scale variation is a very important feature in precipitation extremes. There appear to be no identifiable trends in extreme precipitation (either frequency or intensity) during the last century. The only exception is the upward trend in the number of heavy autumn snowfall events (snowfall in autumn contributes to about 27% of annual total snowfall for Canada). The increasing trend in precipitation during the last century was mainly due to increases in the number of nonheavy events.

4. Spatial characteristics of heavy precipitation

a. *Homogeneous regions and temporal variabilities in the number of heavy events*

The results of K-means clustering of station time series of number of heavy rainfall and snowfall events are displayed in Fig. 8. It was found that four clusters best represent the regional characteristics of heavy rainfall during spring. Summer heavy rainfall events were too noisy to cluster. Two clusters were best to delineate homogeneous regions for rainfall and snowfall in other seasons. It is realized that this type of clustering procedure has some limitations; however, it does represent a practical way of efficiently and effectively identifying stations and regions with reasonably consistent time series characteristics. It is assumed that the variability of extreme events at timescales longer than a decade should be spatially homogeneous. Continuous regions are therefore determined by clusters subject to minor manual adjustment as indicated by demarcation lines depicted in Fig. 8.

Regional heavy daily precipitation indices, computed

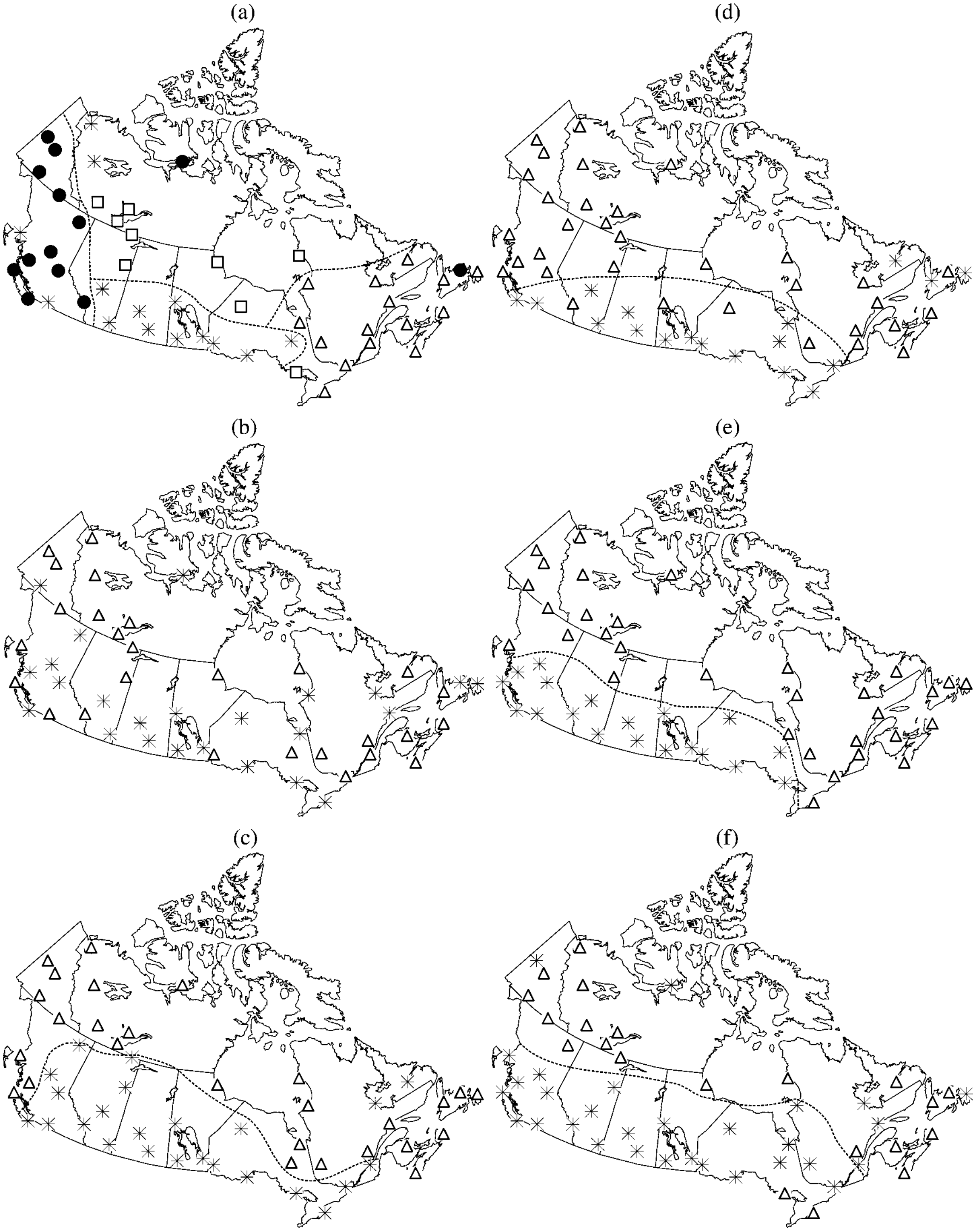

FIG. 8. Station clusters for heavy rainfall events (left panel) during (a) spring, (b) summer, and (c) autumn and, for heavy snowfall events (right panel) during (d) spring, (e) autumn, and (f) winter. Dashed lines delineate regions for regional indices computation.

as the averages of the number of events within the region defined by demarcation lines, reveal marked differences among various regions. Figure 9 shows spring heavy rainfall indices for the four regions defined in Fig. 8a. Interdecadal variability is clearly evident in the number of spring heavy rainfall events over eastern Canada (Fig. 9d). This includes a higher number during the 1950s and 1980s, and lower numbers during the 1960s and

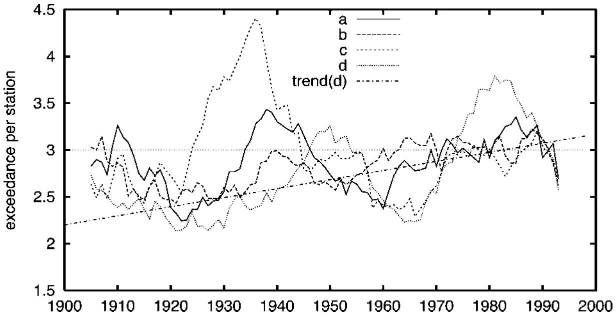

FIG. 9. The 11-yr moving averages of time series of average number of spring heavy rainfall events for the four regions: (a) western (British Columbia and Yukon), (b) central south, (c) central north, and (d) eastern. Dash–dot line represents a significant linear trend (a 20% increase during the 99 yr) over eastern region.

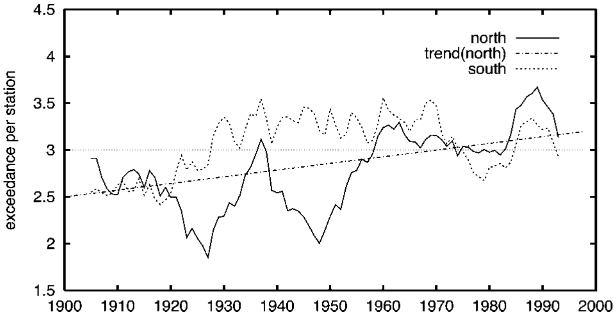

FIG. 11. Same as in Fig. 10 but for autumn heavy snowfall events. Dash–dot line represents a significant linear trend (a 20% increase during the 99 yr) in the north.

prior to the 1950s. The series shows a statistically significant increasing trend. The indices do not reveal any statistically significant decreasing or increasing trends in other regions, although they are relatively higher around 1940 and lower around 1960. During autumn, the number of heavy rainfall events in northern and southern regions displayed little change (Fig. 10). One difference is that the indices were lower in the early part of the twentieth century for the northern region, and lower in the last 20 yr for the southern region. Time series of regional indices for heavy snowfall events are shown in Figs. 11, 12, and 13 for autumn, winter, and spring, respectively. A striking feature in these indices for southern regions is the decadal variability. Autumn snowfall indices were slightly higher from 1930 to 1970 (Fig. 11). During winter, the number of heavy snowfall events increased from the beginning of this century until the 1970s and has since decreased (Fig. 12). In spring, the number of heavy snowfall events was highest around the 1950s and lowest in the early and late parts of the twentieth century (Fig. 13). The decrease in the number of both winter and spring heavy snowfall events in the south may be associated with observed increasing temperatures in those seasons (Zhang et al. 2000) and the resultant conversion of snowfall to rainfall. The snowfall indices for northern regions during both autumn (Fig. 11) and winter (Fig. 12) showed strong decadal variability superimposed on statistically significant upward trends. The number of spring heavy snowfall events exhibited little variability, except that they were relatively low around the 1950s and again during the last two decades.

In summary, the preceding has demonstrated that decadal-scale variability is also a dominant feature in the number of heavy daily precipitation events indices at regional scale. Significant trends are limited to only certain seasons/regions. In particular, there appears to be an upward trend in the number of heavy rainfall events for spring over eastern Canada, and in the number of heavy snowfall events for autumn and winter over northern Canada.

b. *Relationship between the amount of precipitation in heavy events versus nonheavy events*

Karl et al. (1996) found that during the twentieth century, there has remained a steady increase in the area of the United States affected by extreme (>2 in.) 1-day precipitation events. Figure 1 of our paper showed trends in this ratio for Canada, but it was felt that it was important to separately compute the linear trend in the fractions of rainfall and snowfall occurring as heavy events. Lack of sufficient data over the north prevents examination of heavy precipitation over all of Canada during the entire twentieth century. Nevertheless, there

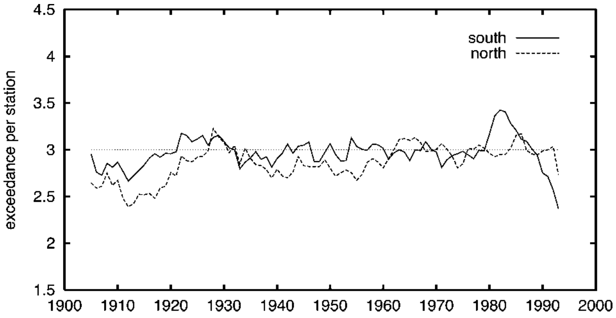

FIG. 10. The 11-yr moving averages of time series of average number of autumn heavy rainfall events for south and north regions.

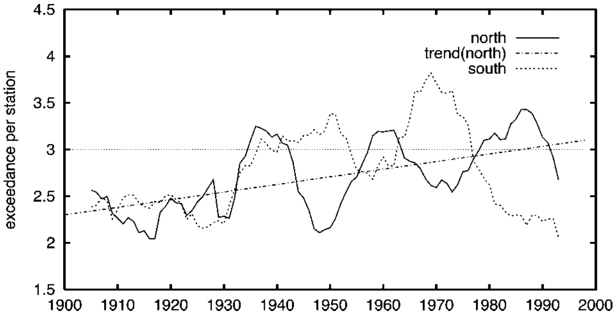

FIG. 12. Same as in Fig. 11 but for winter heavy snowfall events.

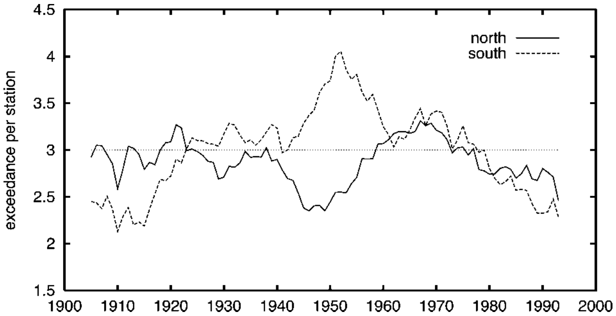

FIG. 13. Same as in Fig. 10 but for spring heavy snowfall events.

has been adequate station coverage since the 1950s to allow for a comprehensive analysis during the last 49 yr (1950–98). In this and following subsections, we have used data for all 68 stations covering 1950–98.

The sign and significance of trends of fractions of rainfall and snowfall falling in heavy events are shown in Fig. 14. They generally agree with the previous analyses of heavy rain and snow frequency. Areas with an increase in the frequency of heavy events are associated with an upward trend in the fraction of precipitation occurring as heavy events. Only a few stations show a significant trend for heavy rainfall. On the other hand, heavy snowfall shows significant and spatially consistent upward trends during autumn, winter, and to a lesser extent spring. The majority of positive trends occur over northern Canada.

As indicated in section 3c and in Fig. 7, changes in annual precipitation over Canada are mainly due to an increase in nonheavy events. To provide a better understanding and a spatial perspective of these changes, correlations between precipitation occurring in heavy versus nonheavy events are computed (Fig. 15). A significant positive correlation exists between total amount of snowfall contributed by heavy events and that by nonheavy events at most stations, especially, in the west. This signifies that for these three seasons, the amount of snow falling as heavy and nonheavy events has remained more or less proportional. The relationship between rain falling in heavy and nonheavy events is, however, not as strong or spatially consistent as snowfall. These differences likely reflect the different mechanisms for generating heavy daily snowfall and rainfall. Most heavy rainfall events (as defined here) are associated with strong convection and therefore do not necessarily require large synoptic-scale systems for initiation. As a result, the rainfall events are less dependent on mean storm tracks than the more synoptic-scale-dominated snowfall events.

c. Trends in the amount of heavy precipitation

The spatial distribution of linear trends in the magnitude of the 90th percentile of annual daily rainfall, snowfall, and precipitation are presented in Fig. 16. Over the last 49 yr, the 90th percentile of daily precipitation has slightly increased over a large portion of the country, with the exception of southern regions and the Yukon. However, only a few small areas show statistically significant trends. This is consistent with Mekis and Hogg (1999), who also found that the fraction of precipitation in Canada falling in heavy events has increased during 1946–95, but this was due exclusively to increases in the north. The spatial distribution of linear trends in the 90th percentile of daily snowfall is similar to that of total precipitation, except that the upward trend covers a much larger area. The trend in the 90th percentile of daily rainfall also shows a mix of positive and negative trends. However, they are generally not significant. Significant negative trends occur over northwestern Canada. It appears that the increase in extreme precipitation in the last 49 yr is related more to an increase in extreme snowfall events as opposed to heavy rainfall. A separate investigation of individual time series has shown that the largest events in the precipitation distribution occur as rain; however, a change in the more moderate snow events affects both the shape of the distribution and the value of the 90th percentile. This results in a change in the 90th percentile trend. This further demonstrates the difficulties of combining rain and snow events in extreme event analysis and emphasizes the importance of treating them separately. The strong positive correlation between heavy and nonheavy snowfall events (Fig. 15) indicates that the increase in the heavy snowfall events (and hence the increase in heavy precipitation) is also related to an increase in total snowfall in northern Canada.

5. Discussion and conclusions

The spatial and temporal characteristics of heavy rainfall and snowfall events in Canada have been examined. It was found that decadal variation is a dominant feature in the precipitation extremes. There appears to be no change in either the frequency or intensity of extreme precipitation for the country as a whole during the last century. The lack of generally increasing trend in heavy and extreme events over the last century in this high-latitude country fails to support GCM projections, possibly due to the relatively early stage of greenhouse gas–induced global warming. As well, both national and regional time series of extreme events exhibited strong interdecadal variability, which will increase the difficulty of identifying greenhouse gas–induced changes. The observed upward trend in precipitation totals (Zhang et al. 2000) was mainly due to increases in the number of small-to-moderate rainfall and snowfall events. It was also found that temporal variations in the number of heavy events are generally spatially coherent and quite different for individual seasons and/or regions. There appears to be upward trends in the number of heavy rainfall events for the spring over eastern Canada and in the number of heavy snowfall events for autumn

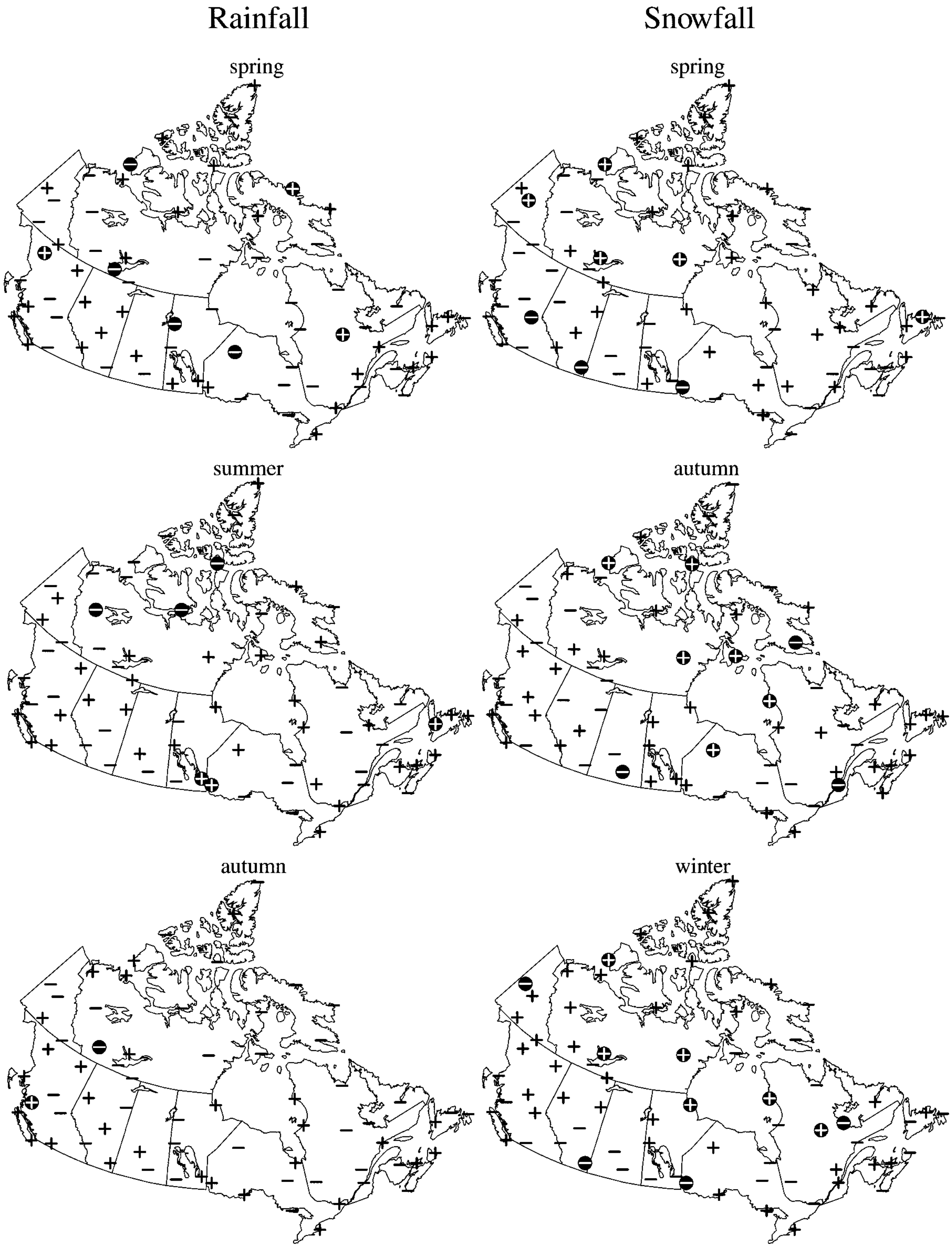

FIG. 14. Trends in the fraction of rain (left) and snow (right) falling in heavy events for the period 1950–98 for different seasons. Positive/negative signs indicate positive/negative trends. Stations with significant trends are marked by filled circles.

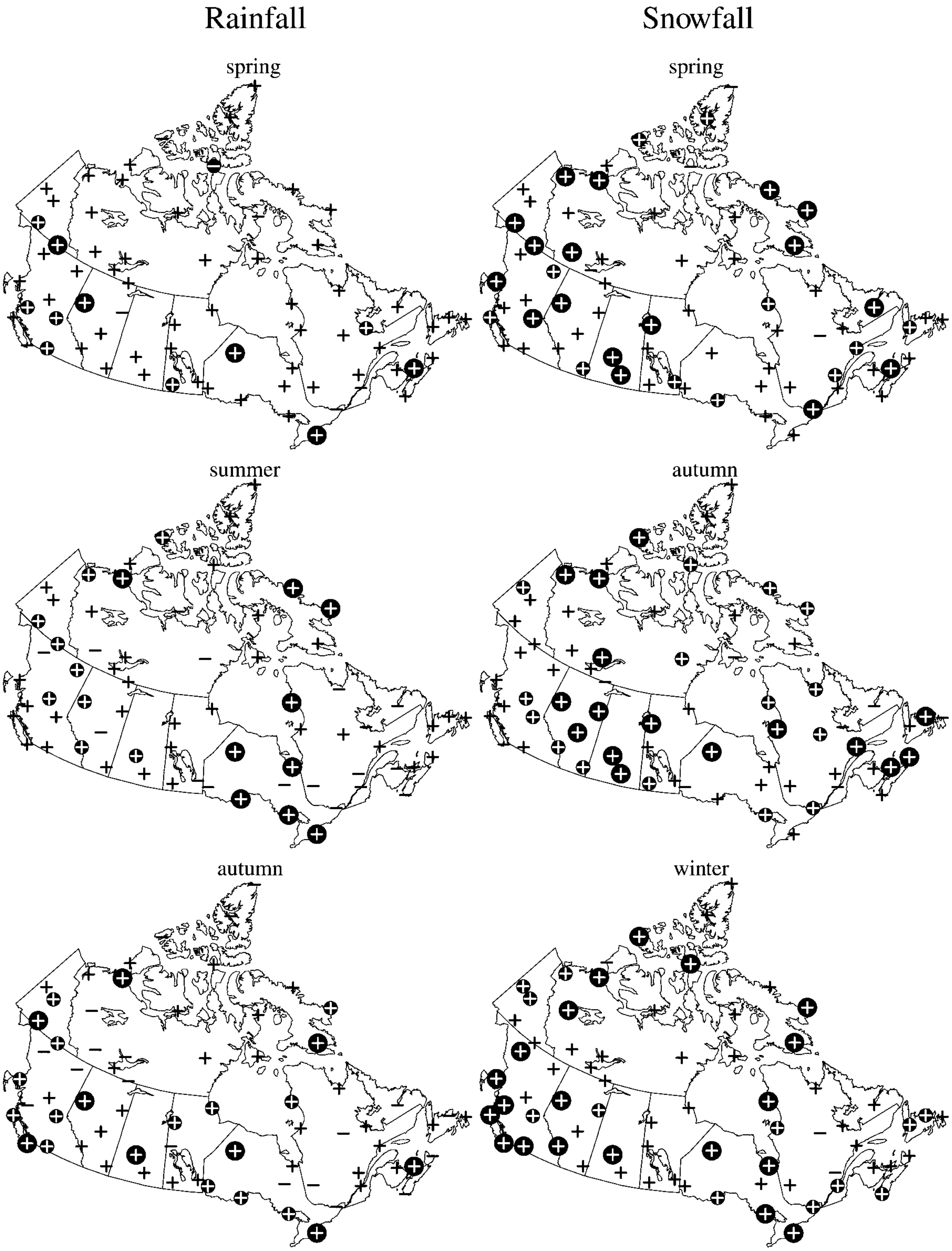

FIG. 15. Signs of correlation between precipitation amounts of heavy events vs nonheavy events for rainfall (left) and snowfall (right). Stations with correlations significant at 1%, 5%, and 10% are indicated as large, medium, and small filled circles, respectively.

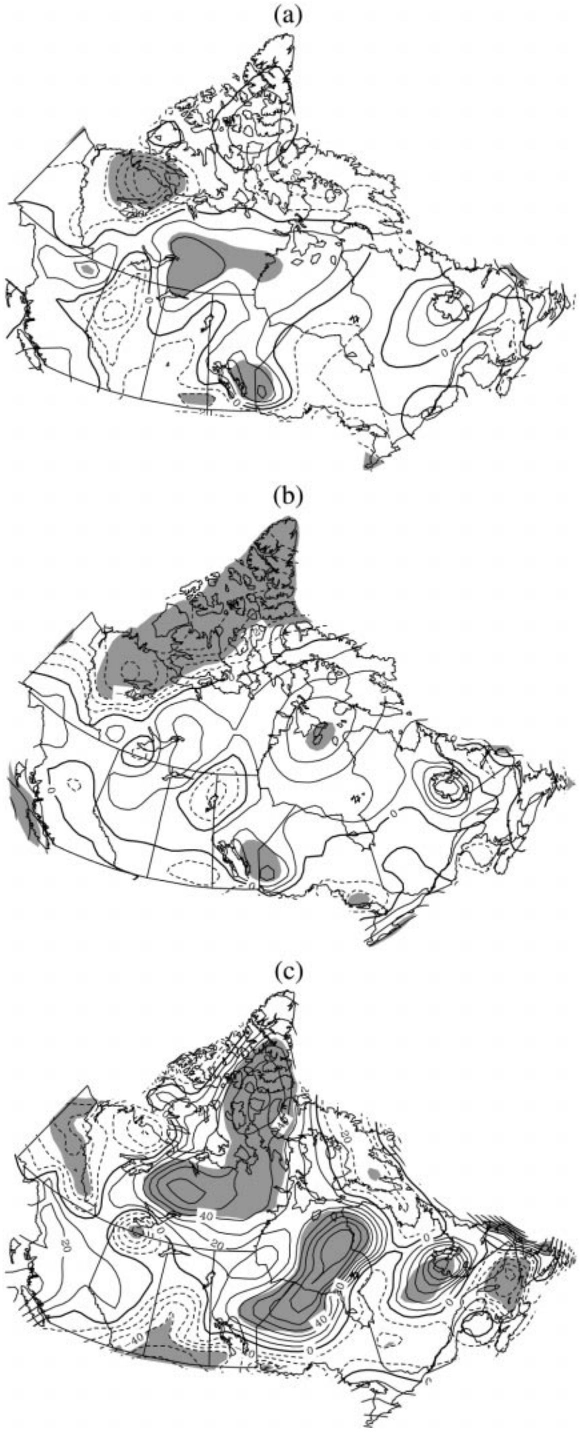

Fig. 16. Linear trends in the magnitudes of the 90th percentiles of daily (a) precipitation, (b) rainfall, and (c) snowfall during 1950–98. Areas with trends significant at the 5% level are shaded. Units are percentage change over the 49-yr period.

and winter over northern Canada. This latter is consistent with observed increases in below-freezing temperatures in northern Canada, presumably associated with increases in available atmospheric moisture (Davis et al. 1999). Characteristics of heavy precipitation are influenced by both heavy rainfall and snowfall events even though the most extreme events invariably consist of rain.

Significant positive correlations exist between the amount of snow falling in heavy events and that in nonheavy events. This suggests a strong linkage between large-scale circulation anomalies and heavy snowstorm occurrences. The implication of such a relationship is important when assessing the possible impact of climate change resulting from increasing CO_2 concentration in the atmosphere. GCMs predict an increase in cold season precipitation, which will likely consist of snow at high latitudes. Thus, global warming may result in both a higher frequency and higher severity of snowstorms in these latitudes. Correlations between the amount of rainfall occurring in heavy events and that occurring in nonheavy events are weak, so that an increase in heavy rainfall events is not necessarily associated with a general increase in all rainfall events. The association between large-scale circulation anomalies and heavy precipitation events requires further investigation.

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