An Overview of the Second Generation Adjusted Daily Precipitation Dataset for Trend Analysis in Canada

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ABSTRACT *A second generation adjusted precipitation daily dataset has been prepared for trend analysis in Canada. Daily rainfall and snowfall amounts have been adjusted for 464 stations for known measurement issues such as wind undercatch, evaporation and wetting losses for each type of rain-gauge, snow water equivalent from ruler measurements, trace observations and accumulated amounts from several days. Observations from nearby stations were sometimes combined to create time series that are longer; hence, making them more useful for trend studies. In this new version, daily adjustments are an improvement over the previous version because they are derived from an extended dataset and enhanced metadata knowledge. Datasets were updated to cover recent years, including 2009. The impact of the adjustments on rainfall and snowfall total amounts and trends was examined in detail. As a result of adjustments, total rainfall amounts have increased by 5 to 10% in southern Canada and by more than 20% in the Canadian Arctic, compared to the original observations, while the effect of the adjustments on snowfall were larger and more variable throughout the country. The slope of the rain trend lines decreased as a result of the larger correction applied to the older rain-gauges while the slope of the snow trend lines increased, mainly along the west coast and in the Arctic. Finally, annual and seasonal rainfall and snowfall trends based on the adjusted series were computed for 1950–2009 and 1900–2009. Overall, rainfall has increased across the country while a mix of non-significant increasing and decreasing trends was found during the summer in the Canadian Prairies. Snowfall has increased mainly in the north while a significant decrease was observed in the southwestern part of the country for 1950–2009.*

RÉSUMÉ *[Traduit par la rédaction] Un ensemble de données quotidiennes de précipitations ajustées de deuxième génération a été préparé pour l'analyse des tendances au Canada. Les hauteurs quotidiennes des chutes de pluie et des chutes de neige ont été ajustées pour 464 stations en fonction de problèmes connus comme la sous-capture due au vent, l'évaporation et les pertes par mouillage pour chaque type de pluviomètre, l'équivalent en eau de la neige selon des mesures avec une règle, les observations de traces et les hauteurs accumulées de plusieurs jours. Les observations de stations situées à proximité ont parfois été combinées pour créer des séries chronologiques plus longues et donc plus utiles pour les études de tendance. Dans cette nouvelle version, les ajustements quotidiens constituent une amélioration par rapport à la version précédente parce qu'ils sont dérivés d'un ensemble de données étendu et d'une meilleure connaissance des métadonnées. Les ensembles de données ont été mis à jour pour inclure les années récentes, y compris 2009. L'effet des ajustements sur les hauteurs totales et les tendances des chutes de pluie et des chutes de neige a été examiné en détail. En raison des ajustements, les hauteurs totales de pluie ont augmenté de 5 à 10% dans le sud du Canada et de plus de 20% dans l'Arctique canadien, comparativement aux observations originales, alors que l'effet des ajustements sur les chutes de neige était plus important et plus variable à travers le pays. La pente des lignes de tendance de la pluie a diminué par suite de la plus forte correction appliquée aux pluviomètres plus anciens alors que la pente des lignes de tendance de la neige a augmenté, surtout le long de la côte ouest et dans l'Arctique. Finalement, les tendances annuelles et saisonnières des chutes de pluie et des chutes de neige basées sur les séries ajustées ont été calculées pour 1950–2009 et 1900–2009. Dans l'ensemble, les chutes de pluie ont augmenté dans le pays alors qu'on a trouvé un mélange de tendances non significatives à la hausse et à la baisse durant l'été dans les prairies canadiennes. Les chutes de neige ont augmenté principalement dans le nord alors qu'une diminution marquée a été observée dans la partie sud-ouest du pays pour 1950–2009.*

KEYWORDS precipitation; rainfall; snowfall; climate records; trends

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1 Introduction

Reliable climate datasets are crucial for climate monitoring and the detection of any climate change signal. However, climate observations require a great deal of processing before they are ready for analysis. Each observation needs to be recorded, transmitted, digitized, quality controlled and then examined by experts familiar with the instruments, observing practices and the climatology. These tasks are becoming even more complex because of the constantly changing observing network, which involves relocation and closure of sites and changes in instruments and practices. As a result, climate data have to be adjusted to address these issues and to ensure continuity of the records for climate monitoring and climate change studies. Methodologies required to adjust climate data have also been improving. When a new version of an adjusted dataset becomes available to the scientific community, it is vital to document the data properly along with the adjustments. Users can then understand the data better and determine if they are suitable for their own analyses.

It is widely recognized that gauge-measured precipitation has a systematic bias mainly caused by wind-induced undercatch, wetting losses (water adhering to the surface of the inner walls of the gauge that cannot be measured by the volumetric method) and evaporation losses (water lost by evaporation before the observation can be made). In 1985, the World Meteorological Organization (WMO) initiated the Solid Precipitation Measurements Intercomparison project to assess and document the national methods of measuring solid precipitation (Goodison et al., 1998). Corrections have been applied to a large number of stations located in the High Arctic: gauge-measured precipitation amounts for these stations have increased by about 10% for the summer and from 80 to 120% for the winter (Yang et al., 2005). In a study by Ding et al. (2007), it was noted that bias correction can change the magnitude and even the direction of a trend. Detailed documentation of the instruments, including their type, location and environment, is crucial since measurements can be affected by many changes during a station's history. The Meteorological Service of Canada (MSC) has used a number of different gauges for measuring rainfall over the past 150 years (Metcalfe et al., 1997). When the recently introduced rain-gauges were compared to the traditional gauges and to the WMO reference pit gauge (WMO, 1972), the results of the comparison indicated that the manual Type B gauge, in service since the 1970s, provided the most accurate measurements compared to the pit gauge data (Devine and Mekis, 2008).

In the mid-1990s, the first generation Adjusted Precipitation for Canada - Daily (APC1-Daily) dataset was prepared to provide a more accurate estimate of the precipitation amount and for the analysis of climate trends (Mekis and Hogg, 1999). Daily rainfall and snowfall were adjusted sezparately for 495 locations across the country. For each type of rain-gauge, corrections to account for wind undercatch as well as evaporation and wetting losses were implemented. For snowfall, ruler measurements were used throughout the entire period and a density correction based on a set of coincident ruler and Nipher gauge observations was applied to all ruler measurements. An adjustment was performed to account for trace observations of both rain and snow. Finally, neighbouring observations were sometimes joined and adjustments were applied based on a simple ratio computed using available periods of overlapping data. The APC1-Daily dataset was used in several studies, including temperature and precipitation trends in Canada (Zhang et al., 2000), changes in temperature and precipitation indices in Canada (Vincent and Mekis, 2006) and global changes in daily extreme temperature and precipitation (Alexander et al., 2006).

A number of improvements were introduced in the second generation datasets. The station list was revised to include stations with longer periods of observations. The rain-gauge adjustments were derived from more field experiments. The adjustment map for the snow water equivalent from ruler measurements was improved since it was based on 175 stations compared to the previous 63 stations. More background information was retrieved from the metadata for a better adjustment of trace observations. The accumulated amount flags, indicating that precipitation had fallen over a few days and was reported on the last day of the event, were taken into account. Joined stations were further tested using neighbouring stations to determine whether an adjustment was required.

The primary objective of this paper is to document all the procedures used to produce the second generation Adjusted Precipitation for Canada - Daily (APC2-Daily) dataset to ensure transparency to all users. To assist users in their analyses and the proper interpretation of results, it is important that all the information is merged into a single manuscript to provide an adequate understanding of the data. The second objective is to assess the impact of the adjustments on rainfall and snowfall amounts and the magnitude of the trends. The final objective is to present an updated analysis of annual and seasonal trends using this newest generation of datasets, which includes a longer period of time (to 2009). Section 2 presents the data and Section 3 describes the adjustments for known measurement issues and their impact on accumulated amounts and trends. Section 4 explains the adjustments for joined station observations. The trends in annual and seasonal rainfall and snowfall are presented in Section 5. Lastly, a summary is provided in Section 6.

2 Data

Daily rainfall gauge and snowfall ruler data were extracted directly from the National Climate Data Archive of Environment Canada. Adjusting rain and snow separately allows the correction of known problems such as instrument deficiencies and changes in observing procedures. All rainfall and snowfall measurements used in the APC2-Daily dataset were made by observers and no measurements were made by automatic systems. Station history files were searched for metadata information, such as installation dates of the rain-gauges, the introduction date of the 6-hourly and hourly measurement program and dates of station closure and/or relocation. Further metadata information was also provided by national experts in climate observing and climate practices.

Stations with long-term rainfall and snowfall measurements, covering as many of the most recent years as possible were chosen for inclusion in the second generation dataset. Since the 1990s, the climate observing network has changed considerably in Canada because of downsizing of the traditional network and increasing use of automated systems. Stations were often closed and/or relocated; hence, other stations were identified and added to the dataset to ensure the continuity of rainfall and snowfall observations with time. During station selection, consideration was given to Reference Climate Stations (RCS), which includes stations in the Global Climate Observing System (GCOS) Surface Network (GSN), because these stations are protected (i.e., will not close in the future). Station selection and the list of joined stations were finalized, using the expertise of regional climatologists to produce the best representation of precipitation for Canada.

The second generation dataset includes adjusted daily rainfall, snowfall and total precipitation for 464 locations (Fig. 1a). The adjusted daily total precipitation is the sum of the adjusted rainfall and adjusted snow water equivalent. Most of these stations can be found in the first generation dataset; however, some stations had to be removed because of large amounts of missing data at the end of the record or better quality data available for a neighbouring station. In addition, viable stations from the homogenized temperature dataset (Vincent et al., 2002) were added to provide the user community with both temperature and precipitation data at as many common locations as possible. In the second generation dataset, 53 stations were removed and 22 new locations were added. Although this newly developed database has 10% fewer stations than the first generation dataset, it has 23% more data in the last decade (Fig. 1b). The list of stations, along with their locations, can be obtained from the lead author.

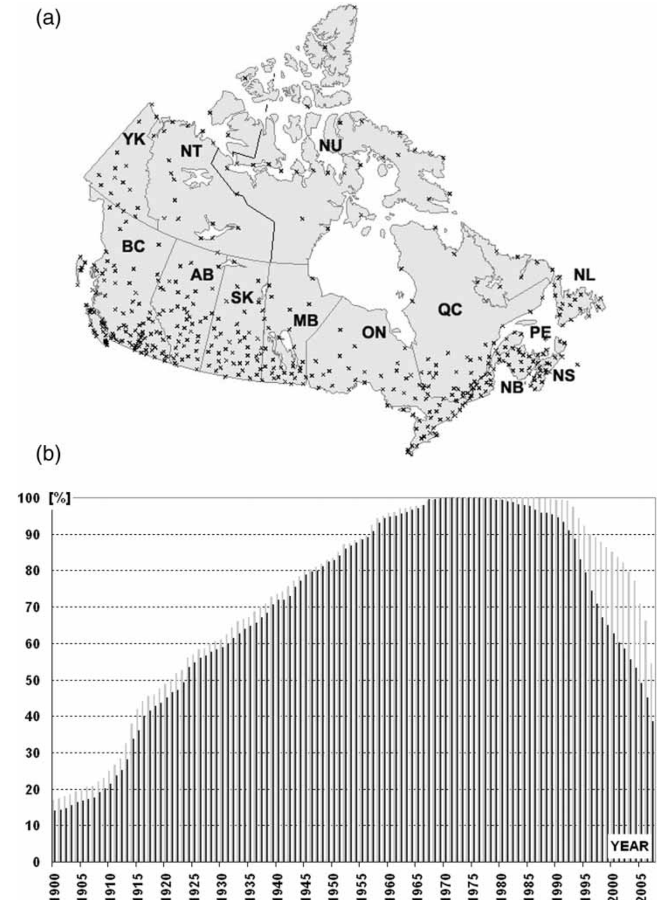

Fig. 1 a) Locations of the 464 stations used in the APC2-Daily dataset and b) percentage of stations with observations for every year: black bars indicate first generation stations (100% represents 495 stations) while grey bars indicate second generation stations (100% represents 464 stations).

3 Adjustments for known measurements issues

a *Adjustments for Rainfall from Rain-Gauges*

The MSC copper gauge, also called the Type A gauge, was originally used in Canada to measure daily rainfall. It was made entirely from copper, but the inside container was modified to soft plastic around 1965. In the 1970s, it was gradually replaced by the Type B gauge at all stations across the country. A complete description of the gauges can be found in Metcalfe et al. (1997) and Devine and Mekis (2008). Adjustments for wind undercatch, evaporation and retention (wetting at the receiver and measuring funnel area) for each type of gauge in the second generation dataset are similar to those applied to the first generation dataset (Mekis and Hogg, 1999); however, they are now based on more field experiments performed at various locations (Devine and Mekis, 2008). Table 1 provides a summary of required daily adjustments for the three major rain-gauges used in Canada during the last century.

Adjustments were applied using the following equation with the values given in Table 1:

$$R_a = (R_m + F_c + E_c + C_c) \times (1 + W_c),$$

where R_a is the adjusted daily rainfall (mm), R_m is the measured daily rainfall (mm), F_c is the funnel wetting correction (mm), E_c is the evaporation from container correction (mm), C_c is the container/receiver retention correction (mm), and W_c is the wind correction factor (%).

The sums of the adjustments in the last row of Table 1 show that the gauges have become more precise over time; therefore, less adjustment is needed for newer gauges. These adjustments were derived from a side-by-side gauge experiment by Routledge (1997) and further described in Devine and Mekis (2008). To avoid the loss of valuable information caused by small-scale corrections required for small rain events, precision of the adjusted daily precipitation dataset was increased from one to two digits after the decimal point.

TABLE 1. Rain-gauge corrections

Type of correction	Unit	Notation	MSC, copper receiver	MSC, plastic receiver	Type B Gauge
1. Wind at Orifice level	%	W_c	0.04	0.04	0.02
2. Wetting at Funnel area	mm d^{-1}	F_c	0.13	0.13	0.08
3. Evaporation	mm d^{-1}	E_c	0.02	0.03	0.01
4. Wetting of Receiver or Container	mm d^{-1}	C_c	0.06	0.03	0.04
Sum of 2, 3 and 4	mm d^{-1}		0.21	0.19	0.13

b *Adjustments for Snowfall from Ruler Measurements*

Because of the availability of many sites with long-term ruler measurements, snow ruler data continue to be used for climate change studies. Historically, for all snow ruler measurements of freshly fallen snow, the liquid precipitation amount (water equivalent) was usually determined by assuming a fresh snow density of 100 kg m^{-3}. This estimate of fresh snow density can be improved because of the availability of coincident Nipher gauge and snow ruler measurements since the 1960s. The procedure was originally applied to the first generation dataset (Mekis and Hogg (1999) based on Metcalfe et al. (1994)) and involves the calculation of ratios of corrected solid Nipher gauge precipitation measurements to snowfall ruler depth measurements when both were operational. The snow water equivalent adjustment factor ρ_{swe} map (Fig. 2) has since been updated using 175 climatological stations with more than 20 years of concurrent observations (Mekis and Hopkinson, 2004; Mekis and Brown, 2010). For quality assurance, the snow water equivalent adjustment factor was verified using observations from independent stations with shorter records that were not originally included in the map production. The updated map allows estimates of ρ_{swe} for ruler-based snowfall observations to be obtained for all long-term climate stations in Canada. The spatial pattern is consistent with processes that influence the density of fresh snowfall and its initial settling, with values ranging from more than 1.5 in the Maritimes to less than 0.8 in south central British Columbia.

c *Adjustments for Flags*

Trace precipitation, flag "T", is less than the minimum measurable amount and is assigned a value of zero. Trace precipitation is important over vast parts of Canada, with the highest impact occurring in the Arctic, where precipitation amounts are very low and many trace events are recorded. Under these conditions, the sum of all trace amounts becomes a significant portion of the total precipitation.

Trace precipitation has not been observed consistently in time; both its definition and the minimum measurable amount have been modified (Mekis, 2005). During the conversion from the imperial to the metric system around 1977–78, all precipitation values were converted from inches to millimetres. Therefore, the minimum measurable amount was changed from 0.01 in (equivalent to 0.254 mm rounded to 0.3 mm) to 0.2 mm for rain measurements and 0.1 in (equivalent to 0.254 cm rounded to 0.3 cm) to 0.2 cm for snow ruler measurements.

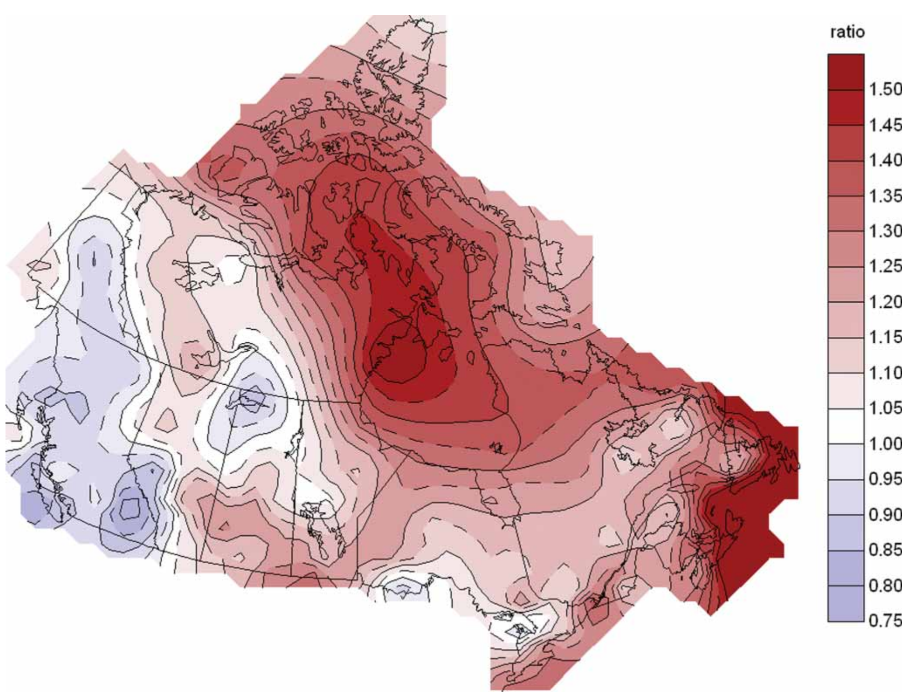

Fig. 2 Updated snow water equivalent adjustment factor (ρ_{swe}) map used for adjusting the snow ruler measurements.

The measurement of trace amounts has not always been practiced. Rainfall trace was mentioned as early as 1871 in an early observer's manual as well as in later manuals in 1878, 1893 and 1914 (Kingston, 1878). However, the next version of the *Instructions to Observers* manual does not contain any reference to the recording of traces of rain (Patterson, 1930). In 1947, trace precipitation was mentioned in the first edition of *Manual of Standard Procedures and Practices for Weather Observing and Recording MANOBS*, effective 1 January 1947 but only under Synoptic Reports (Meteorological Division, 1947). Finally, in Amendment No. 8 of the third edition of *MANOBS*, effective 9 June 1954, the first official mention of the trace flag appeared (Meteorological Division, 1951). Another definition appears in the booklet *How to Measure Rainfall* (Department of Transport, Meteorological Branch, 1955).

There are other reasons for trace observations not being consistent over time. New observers with different training or experience and the number of observations taken daily can affect the number of trace events reported annually. At synoptic stations (mostly airports), observations were taken twice daily prior to January 1941 and four times daily thereafter. Similarly, at climatological stations (volunteer stations), observations are taken twice daily but sometimes they are only taken once in the morning. For proper adjustment of the frequency of trace events, the number of daily and 6-hourly trace flag observations was compared with the Trace Occurrence Ratio calculated from overlapping synoptic and daily archive data (Mekis and Hogg, 1999).

Different adjustments were applied for rain and snow traces. For rainfall traces, amounts between 0.0 and 0.2 mm were considered equally probable and the average of 0.1 mm was applied. Adjustment for solid trace precipitation is more complex and is related to ice crystal events (Mekis and Hogg, 1999). Ratios of the number of ice crystal events to the number of solid precipitation trace events were computed using 6-hourly weather-type information (i.e., rain, ice crystal and snow traces) and mapped for many stations. This map was used to generate the trace adjustment factor for solid precipitation, with values ranging from 0.07 mm in the south to 0.03 mm in the High Arctic, which corresponds to amounts suggested by Metcalfe et al. (1994).

Even if trace amounts were carefully adjusted using all known metadata, it is possible that they could still cause artificial inhomogeneities in time series with low amount of precipitation. Inhomogeneities become less pronounced when a greater amount of precipitation is analyzed. To illustrate, precipitation series for the station at Campsie, Alberta, are presented in Fig. 3. The annual rain, snow and total precipitation calculated from events with less than 0.5, 5 and 10 mm are given in Figs 3a, 3b and 3c, respectively. There is a jump in the number of daily trace events in 1945 (Fig. 3d), which can be detected in the graph of total amounts calculated from events with less than or equal to 0.5 mm events of precipitation (Fig. 3a). However, this jump is not visible at higher thresholds.

It is important to note that although the value of trace precipitation is not zero after the adjustment is performed, it has to be excluded from the computations of some of the indices, such as the number of days with precipitation or the maximum consecutive dry days, because trace precipitation does not generally alleviate dry conditions.

Accumulated precipitation, flag "A", is recorded on the last day of a series of consecutive days with flag "C" (precipitation occurred) or flag "L" (precipitation may or may not have occurred). This situation can happen when an observer is absent for a few days (typically over a weekend) or for an extended period of time. However, the occurrence of an accumulated value does not happen very often and never occurs at some stations. Since daily observations can be used to prepare climate change indices or compute precipitation extremes, it is crucial that the accumulated value is taken into account to prevent further propagation of erroneous values. In APC2-Daily, flags "A", "C" and "L" are retained for further use and their corresponding value is replaced by the accumulated amount divided by the number of affected days; this is done to preserve the monthly total and minimize the impact on extreme values.

d *Impact of Adjustments for Known Measurement Issues*

To illustrate the impact of the adjustments, the relative change in annual total precipitation (%) and the trend for the entire period (mm decade^{-1}) are given after each adjustment for five stations representing different climate regions of Canada (Table 2 and Fig. 4). The two coastal stations, Port Hardy, British Columbia, and Gander, Newfoundland (Fig. 4a), have relatively high annual total precipitation (Table 2) whereas the Arctic station, Resolute, has low annual total precipitation with a high frequency of trace events (an average of 190 trace events a year). Island Falls is located in the relatively dry northwestern forest area while London is in a productive agricultural sector within the Great Lakes region.

In Figs 4b to 4f, four series are generated for each station. First, the annual total precipitation calculated from the original non-adjusted rainfall and snowfall (line 1), along with the best fit linear trend, and the annual total precipitation obtained after applying the rain-gauge correction (line 2) are plotted. Results indicate that the percentage change in the total amount of annual precipitation is similar for the five stations, varying from 3.5 to 4.9% (Table 2), and the trend slopes decreased because of the larger adjustments applied to the older rain-gauge for the periods of time indicated. When the snow water equivalent adjustment is performed (line 3), the total amount of annual precipitation increased at Resolute (30.4%) and Gander (20.8%), because of the larger snow water equivalent adjustment factor (ρ_{swe}) for these two stations (Fig. 2) and decreased slightly at Port Hardy, where the adjustment is less than one (Table 2). The slope of the trend depends on the actual snowfall amount and because ρ_{swe} is consistent throughout the entire period, this adjustment did not affect the trend much. The last adjustment is for the trace flags (line 4). The correction for trace values is always positive, an additional amount of precipitation is added to the observations whenever a trace flag occurs. The impact of trace corrections is dependent on the frequency of this observation at each station and its relative contribution to the annual total

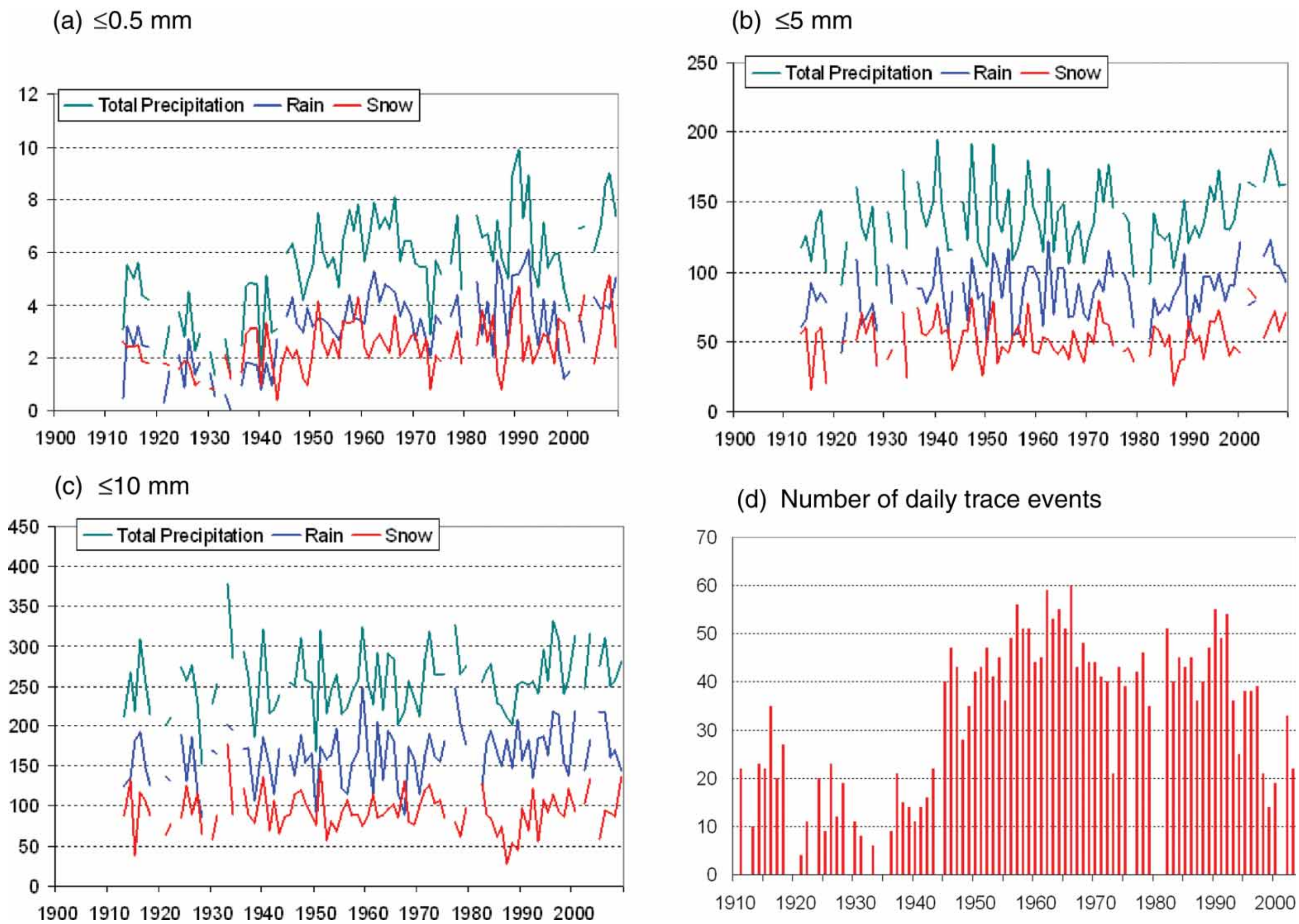

Fig. 3 Annual rain, snow and total precipitation (mm) calculated from events a) ≤0.5 mm; b) ≤5 mm and c) ≤10 mm at Campsie, Alberta. The number of trace events per year is given in d).

precipitation. In the Arctic, this correction increased the amount of precipitation by an additional 18.4% at Resolute (Table 2). The trend did not change considerably because trace adjustments depend on the frequency and distribution of trace observations with time.

A similar exercise was applied to all 464 stations. The magnitude of the adjustments for known rain and snow measurement issues, using the average ratio (for 1950–2009) of the adjusted annual rain (snow) value to the original rain (snow) value was mapped (Fig. 5). Results indicate that the adjustment for rain is larger in the Far North where the frequency of trace measurements is considerable. Meanwhile, the adjustment for snow is more important in the Arctic and the East Coast since ρ_{swe} increases the water equivalent of snowfall considerably in these regions and decreases the water equivalent of snowfall in the western provinces. The adjustments increased solid precipitation by more than 50% in the North since the original amount was very small. Finally, when all the adjustments were applied, the total precipitation increased almost everywhere across the country except in the mountains in the west (Fig. 5c) mainly because of the lower adjustment required for snowfall.

TABLE 2. Impact of adjustments for known measurement issues at five locations in Canada.

				(1) rain + snow measurements		(2) = (1) + rain-gauge corrections		(3) = (2) + snow density corrections			(4) = (3) + trace corrections	
Station Name	Prov.	Period	Mean annual Prec. (mm)	Amount change (%)	Trend (mm/10yr)	Amount change (%)	Trend (mm/10yr)	ρ_{swe}	Amount change (%)	Trend (mm/10yr)	Amount change (%)	Trend (mm/10yr)
Port Hardy	BC	1944–2008	1834	–	56.5	4.6	46.4	0.9	4.4	47.1	5.2	46.2
Island Falls	SASK	1931–2004	493	–	0.2	4.9	−1.7	1.1	6.8	−2.1	8.3	−2.7
London	ONT	1895–2001	974	–	7.1	4.9	5.5	1.2	9.4	4.8	11.0	5.6
Gander	NFLD	1937–2008	1159	–	50.4	4.3	46.2	1.5	20.8	58.4	23.3	57.3
Resolute	NU	1948–2007	159	–	8.3	3.5	7.7	1.4	30.4	11.4	48.8	13.6

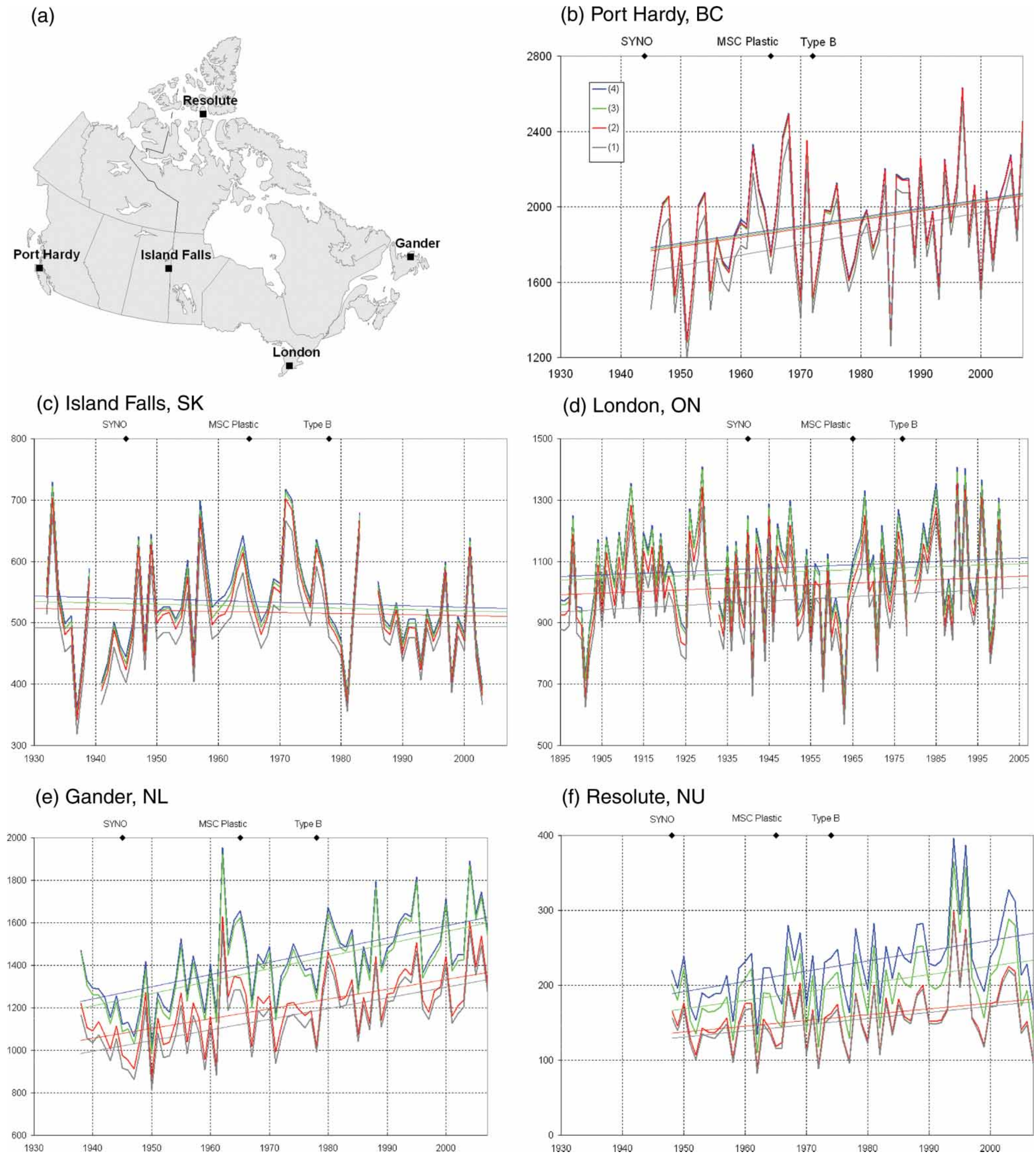

Fig. 4 Annual total precipitation (mm) for five stations: line (1) represents the precipitation total from the original data; line (2) is line (1) + rain-gauge corrections; line (3) is line (2) + snow water equivalent corrections; and line (4) is line (3) + trace corrections.

Rain and snow were adjusted not only to provide more accurate amounts but also to produce a better estimate of the trends. Figure 6 presents the difference in the annual rainfall and snowfall precipitation trends for 1950–2009 before and after the adjustments. This difference in trend was further divided by the mean for the entire period to take into account the climatology of the station (expressed as a percentage). Figure 6a shows that adjustments applied to the daily

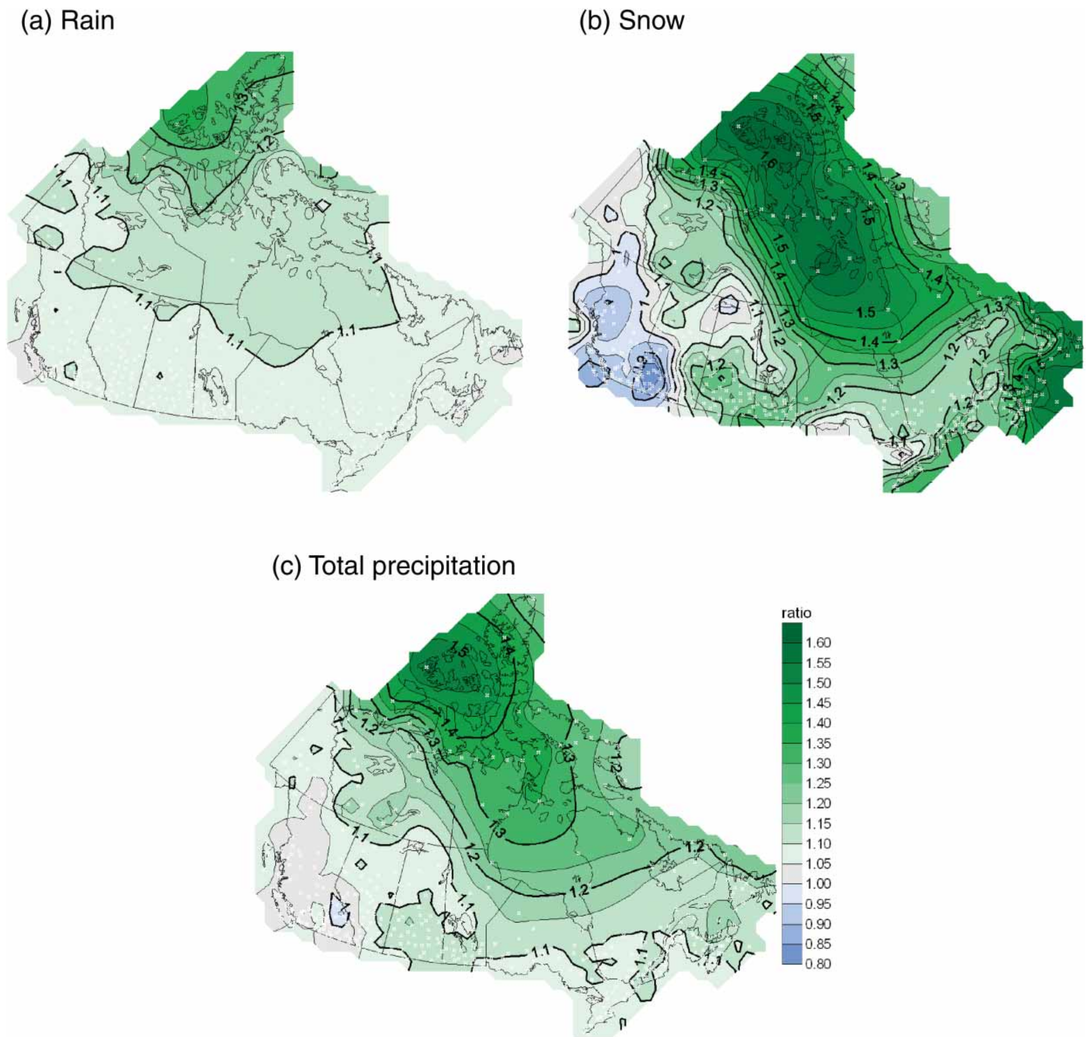

Fig. 5 Magnitude of adjustments for all known rain and snow measurement issues using the average ratio of the annual rain (snow, total) with all adjustments to the original rain (snow, total) measurements from 1950 to 2009.

rainfall decreased the trends by about 5% at many stations across the country. This is mainly because of the larger adjustment factor applied to the older rain-gauges. However, the adjustments increased the snow trends at many northern locations due to the larger adjustments required for trace observations (Fig. 6b).

4 Joining station observations

For many stations, it was necessary to merge observations from nearby stations to produce longer time series of rainfall and snowfall for trend analysis. A procedure to determine if joining precipitation observations created an artificial discontinuity at the joining dates was developed by Vincent and Mekis (2009) and was used to examine the 234 stations. Based on the results, about 35% of the stations were adjusted for rain and 58% of the stations were adjusted for snow (Fig. 7). The magnitude of the adjustment ratio varied from 0.78 to 1.29 for rainfall and 0.64 to 1.45 for snowfall. The adjustments are based on neighbouring stations, which is a major improvement over the first generation dataset where adjustments were applied only if overlapping data were available.

Figure 8 presents the difference in annual rainfall and snowfall precipitation trends before and after all the adjustments were applied, including those for joining stations. The results show that the adjustment for joining does not have a uniform effect on the trends. For example, at Geraldton, Ontario, the slight positive difference in trend in snowfall (Fig. 6b) became negative after adjustments (Fig. 8b). Meanwhile, the slight positive difference in snowfall trend (Fig. 6b) at Beaverdell, British Columbia, became more positive after the adjustments (Fig. 8b).

As previously mentioned, the climate observing network in Canada has changed considerably since the 1990s and will continue to change. Station closures and relocation are ongoing issues. The list of joined stations along with the year of joining can be obtained from the lead author. Due to recent changes, observations were joined at 12.3% of all stations after 1990 in the second generation datasets.

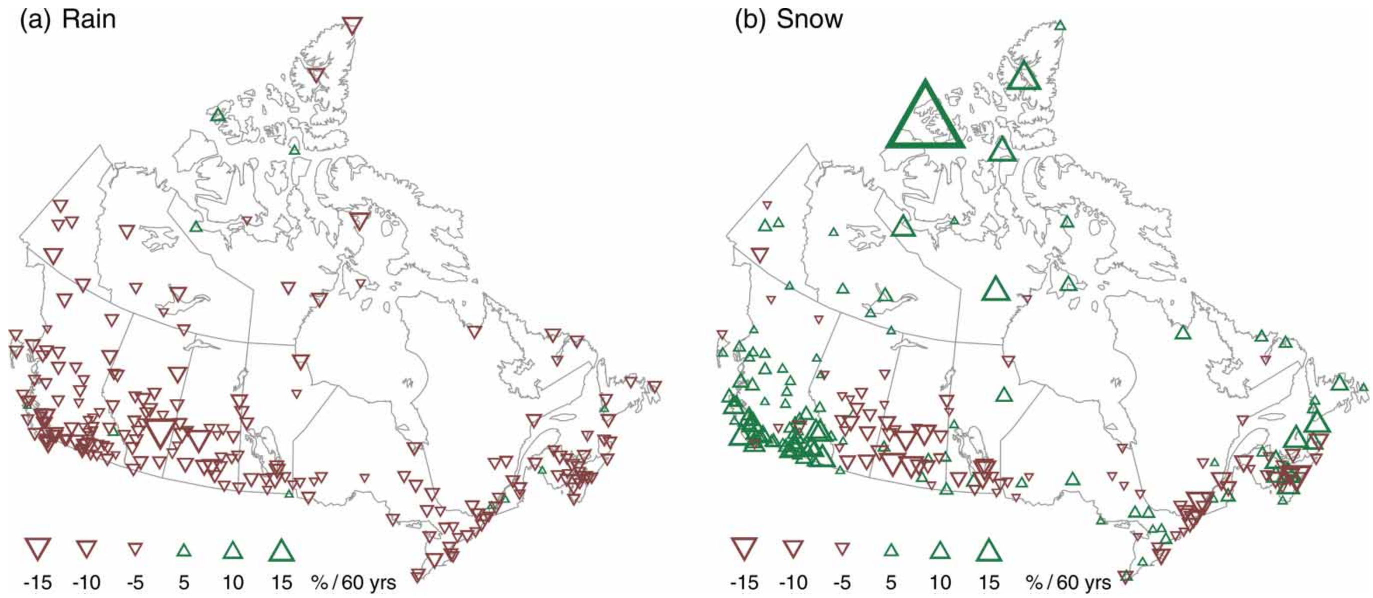

Fig. 6 Difference in the trends in annual total rainfall and snowfall (expressed as a percentage) before and after adjustments for 1950–2009. Panels a) and b) include rain-gauge, snow and trace adjustments. The size of the triangle is proportional to the magnitude of the change in trends.

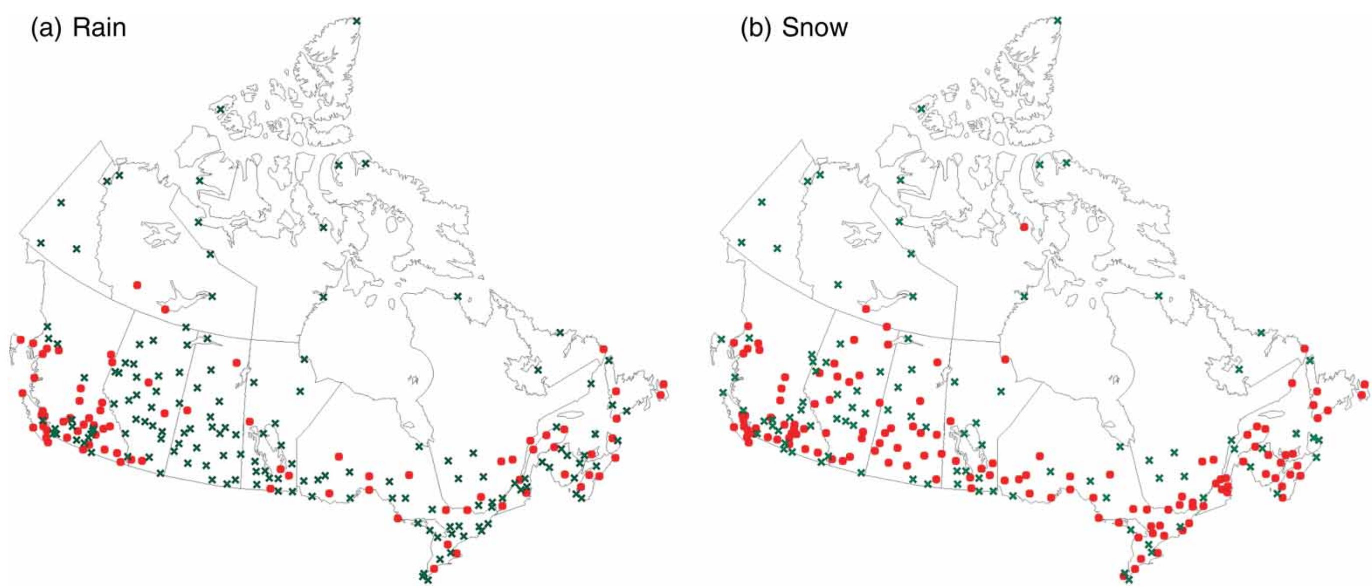

Fig. 7 Location of joined stations for a) rain and b) snow. Green crosses indicate joined stations without adjustments and red dots indicate joined stations with adjustments.

5 Trends in annual and seasonal rainfall and snowfall

Since the climate observing network was not established in northern Canada until the late 1940s, there are many regions in the North with very little data prior to 1945. For this reason, the trends were analyzed for two periods: 1950–2009 for the entire country and 1900–2009 for southern Canada (south of 60°N). Anomalies (expressed as a percentage) were computed at individual stations; these are departures from the reference period 1961–1990, which are further divided by the 1961–1990 mean. Trends were obtained for each station and for the national series representing all of Canada and southern Canada. To generate these last two series, the country was divided into 5°x5° grid boxes, and the national and southern Canada mean series were computed from the average of the stations within the individual boxes. The linear trend was estimated using the approach taken by Sen (1968) and the significance of the trend was determined using Kendall's test (Kendall, 1955). The trend was computed only if more than 80% of the values were present and the statistical significance was assessed at the 5% confidence level.

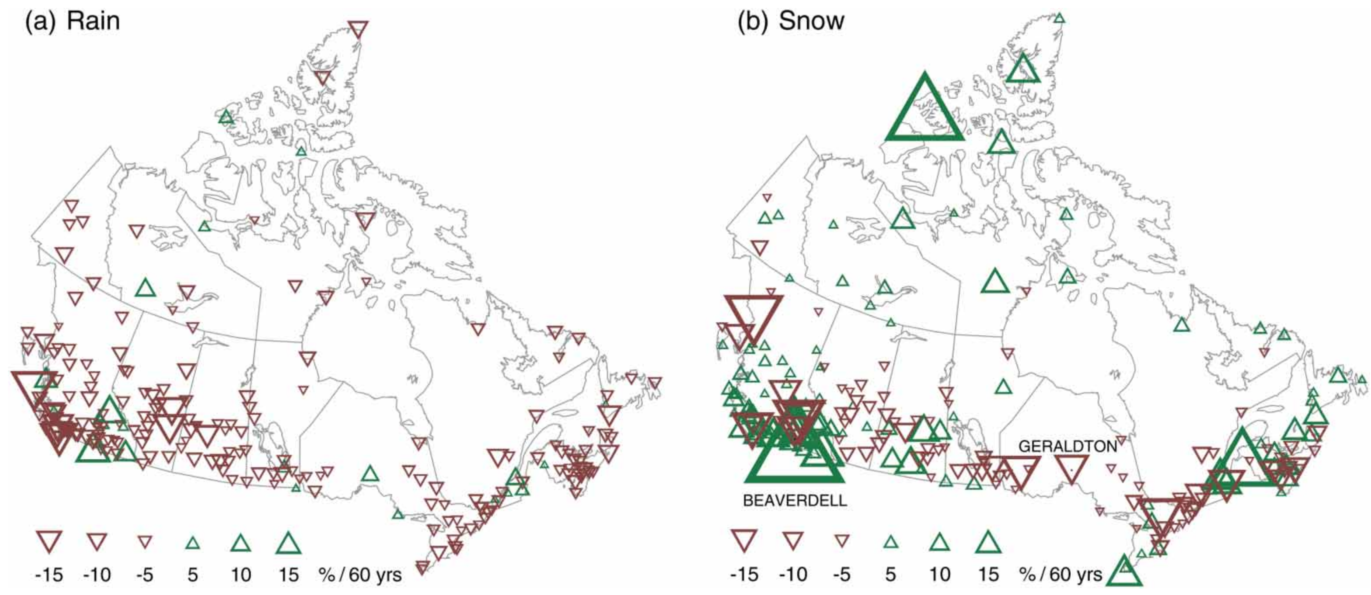

Fig. 8 Difference in trends of annual total a) rainfall and b) snowfall (expressed as a percentage) before and after all adjustments for 1950–2009 including adjustments for joining. The size of the triangle is proportional to the magnitude of the change in trends.

a *Trends for Canada, 1950–2009*

Annual rainfall in Canada increased by about 12.5% from 1950–2009 (Fig. 9a). Positive trends are observed from coast to coast and in the North (Fig. 10a). Even if most of the stations show an increase in annual rainfall during the past 60 years, significant increasing trends of 10 to 30% (depending on location) were found at only 26% of the stations. Overall, rainfall totals have increased in all seasons. The most pronounced increase is observed during the spring when 28% of the stations show significant increasing trends (Fig. 10b). During the summer (Fig. 10c), the pattern of change is less consistent, with many stations in the Canadian Prairies showing non-significant decreasing trends (southern Alberta, Saskatchewan and Manitoba). In the fall (Fig. 10d), significant increasing trends are found mainly in eastern regions including Ontario, Quebec and the Atlantic provinces (New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland).

Annual snowfall in Canada increased slightly, by about 4%, from 1950 to 2009 (Fig. 9b). However, this increase in snowfall has not been consistent either temporally or spatially. The national time series for Canada shows a strong increase in annual snowfall from the 1950s to 1970, which is followed by a substantial decrease until the 1980s with no change up to 2009. Spatially, many stations located in the western provinces (British Columbia, Alberta and Saskatchewan) show significant decreasing trends whereas stations in the North show an increase in annual snowfall (Fig. 11a). With regard to seasonal trends, snowfall decreases in southwestern regions and increases in the North during winter (Fig. 11c) and, to a lesser extent, during spring (Fig. 11d). Furthermore, these changes are less pronounced in fall (Fig. 11b).

b *Trends for Southern Canada, 1900–2009*

Annual rainfall increased by 8.7% from 1900 to 2009 in southern Canada. The national time series for southern Canada indicate a strong decrease until 1920 followed by a steady increase from the 1920s to 2009 (Fig. 9c). This increase in annual rainfall is observed at most stations across the country (Fig. 12a). Although there are fewer stations in southern Canada with enough data to compute the trend from 1900 to 2009 than for the shorter 1950–2009 period, 54% of the long-term stations show a significant increase in annual rainfall with trends varying from 10 to 30% for the 110-year period. More stations were available on the seasonal time scale. Increasing rainfall totals are found across the country during all seasons: significant increasing trends were found in 42%, 31% and 35% of the stations during the spring (not presented), summer (Fig. 12b) and fall (not presented), respectively. A mix of non-significant increasing and decreasing trends is also observed in the Canadian Prairies (mainly southern Alberta, Saskatchewan and Manitoba); this pattern is more evident during summer and fall and less consistent during spring.

Annual snowfall increased slightly, by 6.8%, from 1900 to 2009 in southern Canada. The changes in snowfall are neither temporally nor spatially consistent. The annual snowfall time series for southern Canada shows a steady increase from the 1920s to 1970, followed by a considerable decrease to the 1980s with no major change up to 2009 (Fig. 9d). Spatially, a mix of increasing and decreasing trends is found annually (Fig. 12c). During winter (Fig. 12d), a mix of significant increasing and decreasing trends is observed in the southeastern provinces, with the significant decreasing trends observed at stations located along the more densely populated St. Lawrence River.

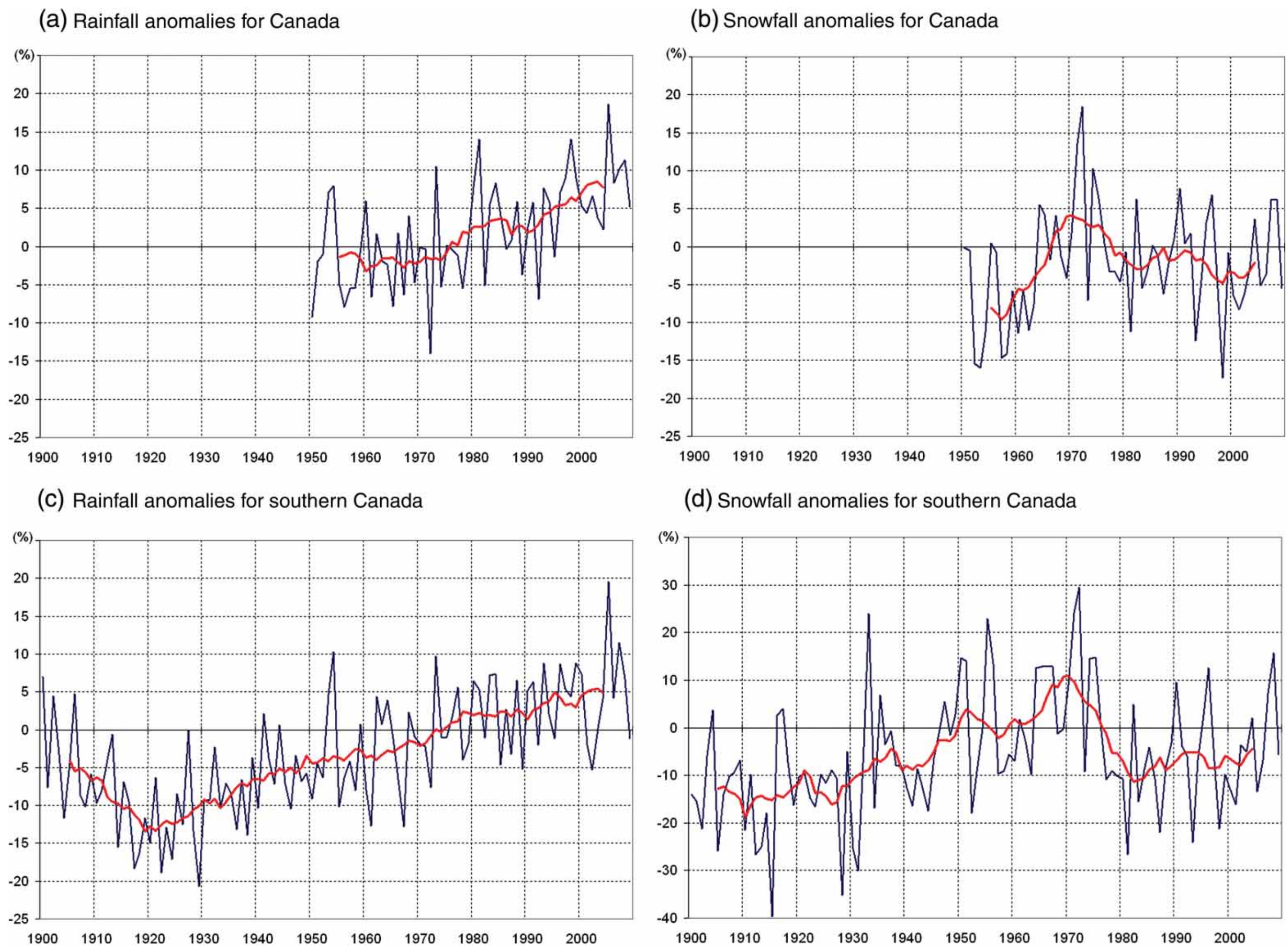

Fig. 9 Rainfall anomalies (expressed as a percentage) for a) Canada, 1950–2009 and c) southern Canada, 1900–2009; snowfall anomalies (expressed as a percentage) for b) Canada, 1950–2009 and d) southern Canada, 1900–2009. The red line represents the 11-year running mean.

6 Summary

Several improvements have been made to the APC2-Daily dataset:

- The station list was revised to include stations with longer periods of observations covering as much of the last 20 years (1990–2009) as possible with daily rain-gauge and snow ruler measurements. The continuity of snowfall observations had become more challenging as the number of stations with snow ruler measurements being taken by observers decreased because of automation.
- Rain-gauge adjustments were based on more field experiments and increased metadata.
- An updated snow water equivalent adjustment factor map, based on almost three times the number of stations as used previously with concurrent snow ruler and Nipher gauge observations, was used to obtain a better estimate of the water content of fresh snow at any location across Canada.
- More information was used to obtain a better adjustment of trace observations, including searches of historical files and analysis of lower than minimum amount versus small amounts of measurable precipitation.
- The accumulated amount was taken into account by distributing it over the affected days. The distributed amount will be further refined using observations from surrounding stations.
- Since overlapping periods are not available at many merged stations, new adjustments were obtained for joined dates from standardized ratios between tested sites and their neighbours. Final adjustments were based on either the test results or overlapping observations.

The impact of the adjustments on precipitation amounts is summarized as follows. Rainfall amount has increased because of the adjustment for rain-gauges. Applying the snow water equivalent adjustment factor increased the snowfall precipitation amount on the East Coast and in northeastern regions and slightly decreased the amount on the West Coast and in western regions. Including trace event adjustments increased the total amount of precipitation; its overall effect depended on its frequency, which varies

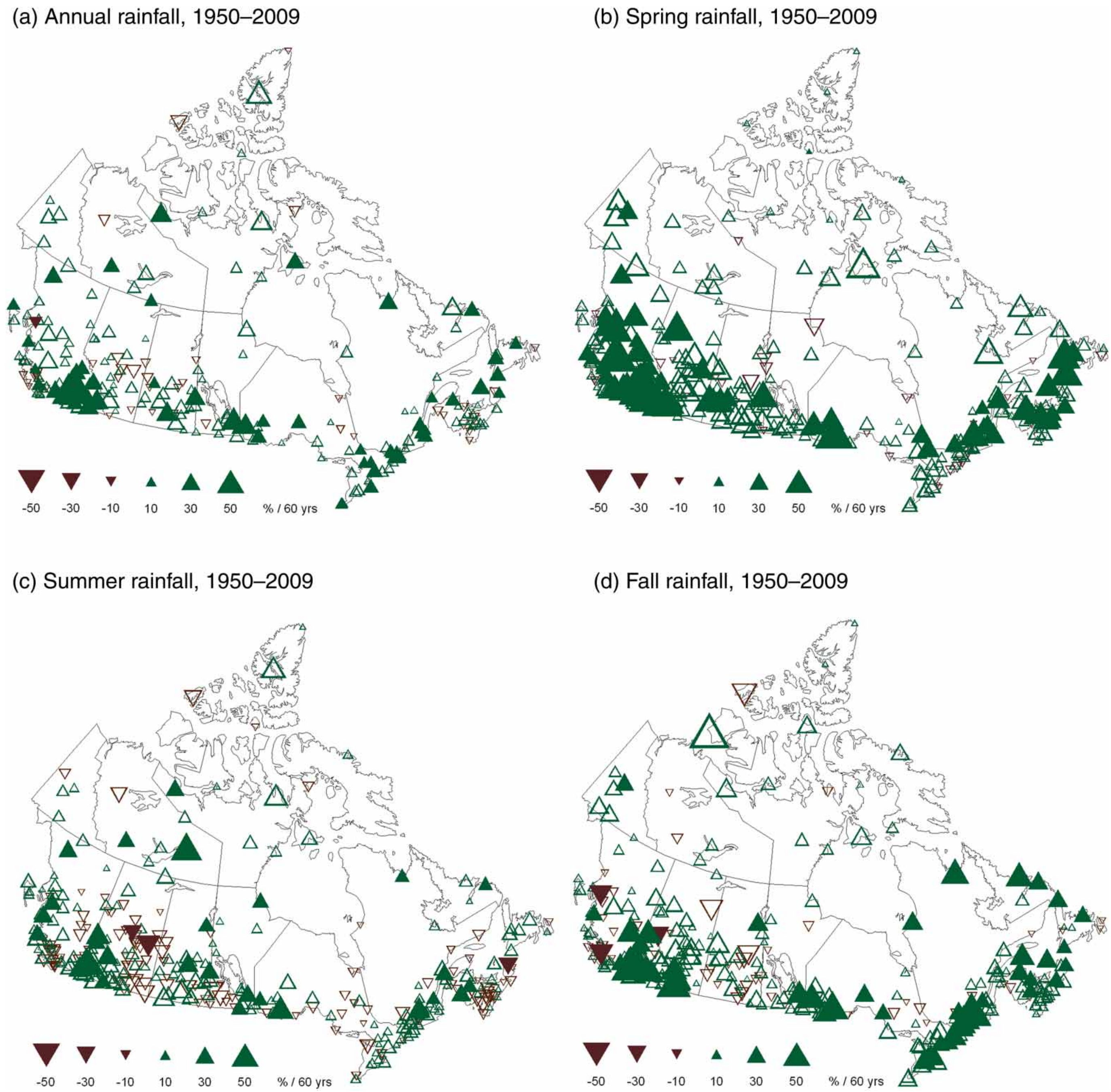

Fig. 10 Trends in annual and seasonal rainfall for 1950–2009. Upward and downward pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

throughout the country. Because of relatively low annual total precipitation and a high occurrence of trace events, rainfall and snowfall amounts increased the most in the North.

The impact of the adjustments on trends varies depending on the element and the climate characteristics of the region. Overall, since adjustments for older gauges are larger, rainfall trends decreased slightly after adjustment. Snow trends became more positive along the West Coast and in the Arctic because of snow water equivalent adjustments applied to snow ruler measurements. Trace corrections did not significantly affect the trends.

Annual and seasonal rainfall and snowfall trends were examined for 1950–2009 and 1900–2009. Overall, rainfall increased across the country during all seasons for both periods; a mix of non-significant increasing and decreasing trends was also found in the summer for the Canadian Prairies. Snowfall increased mainly in the North while a significant decrease was found in the southwestern part of the country for 1950–2009.

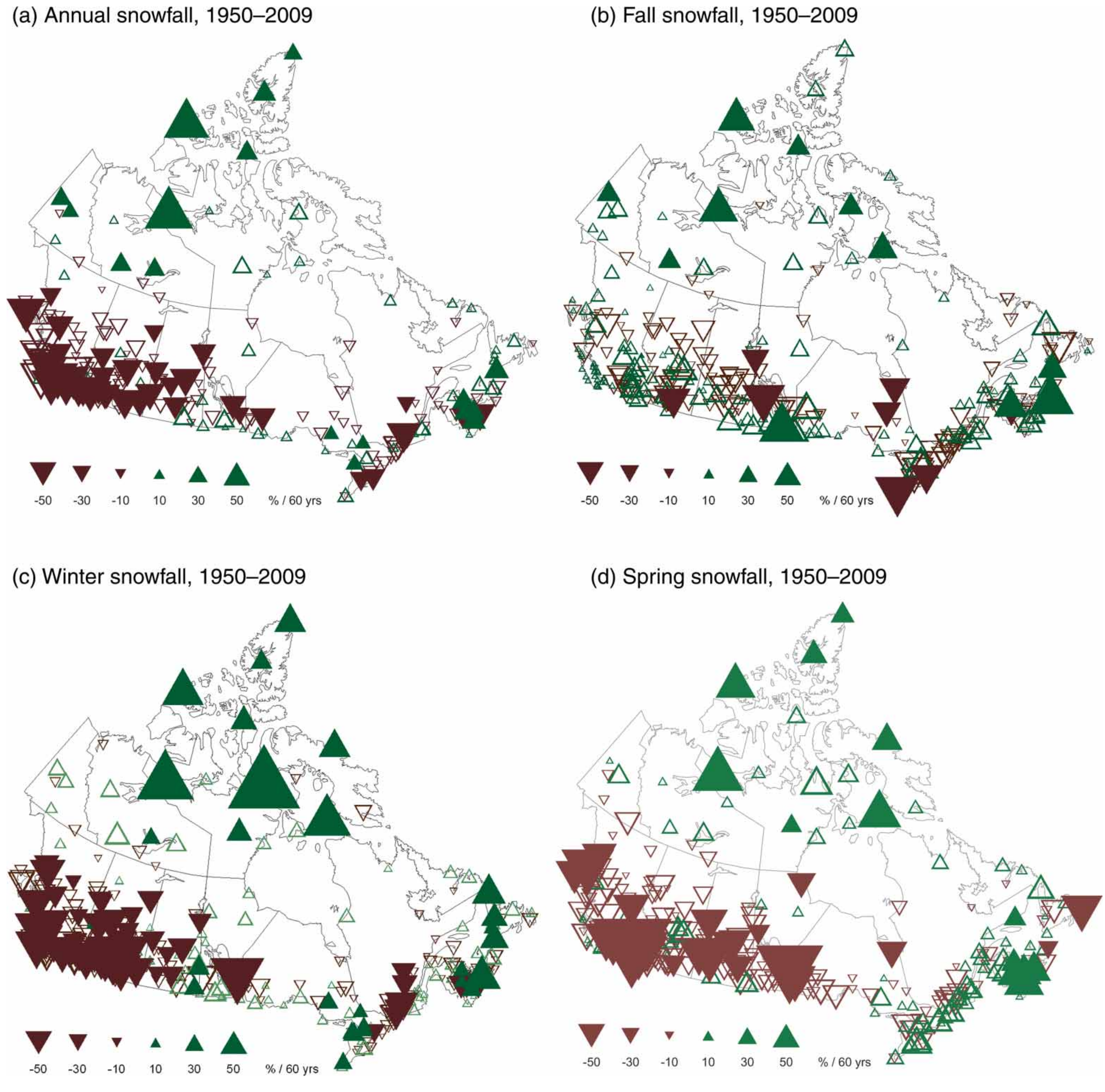

Fig. 11 Trends in annual and seasonal snowfall for 1950–2009. Upward and downward pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

Inhomogeneities due to "unknown" changes have not been resolved in this new version of adjusted precipitation. These include, for example, changes in observing practices, new observers, or any other undocumented change such as the relocation of the rain-gauge a short distance away. In several European studies, homogeneity testing and adjustments were performed on the total precipitation series and inhomogeneities were often caused by the instrument's relocation (Hanssen-Bauer and Førland, 1994; Tuomenvirta, 2001; Wijngaard et al., 2003). In Canada, when a station is relocated, a new identification number is assigned to the new location; consequently, the change is known and data segments can be merged using the documented relocation date.

The main advantage of the procedures presented in this paper is the ability to directly adjust daily rain-gauge and snowfall ruler measurements when they are observed. The adjustments used for the second generation dataset seem to be reasonable when annual, seasonal and monthly totals are

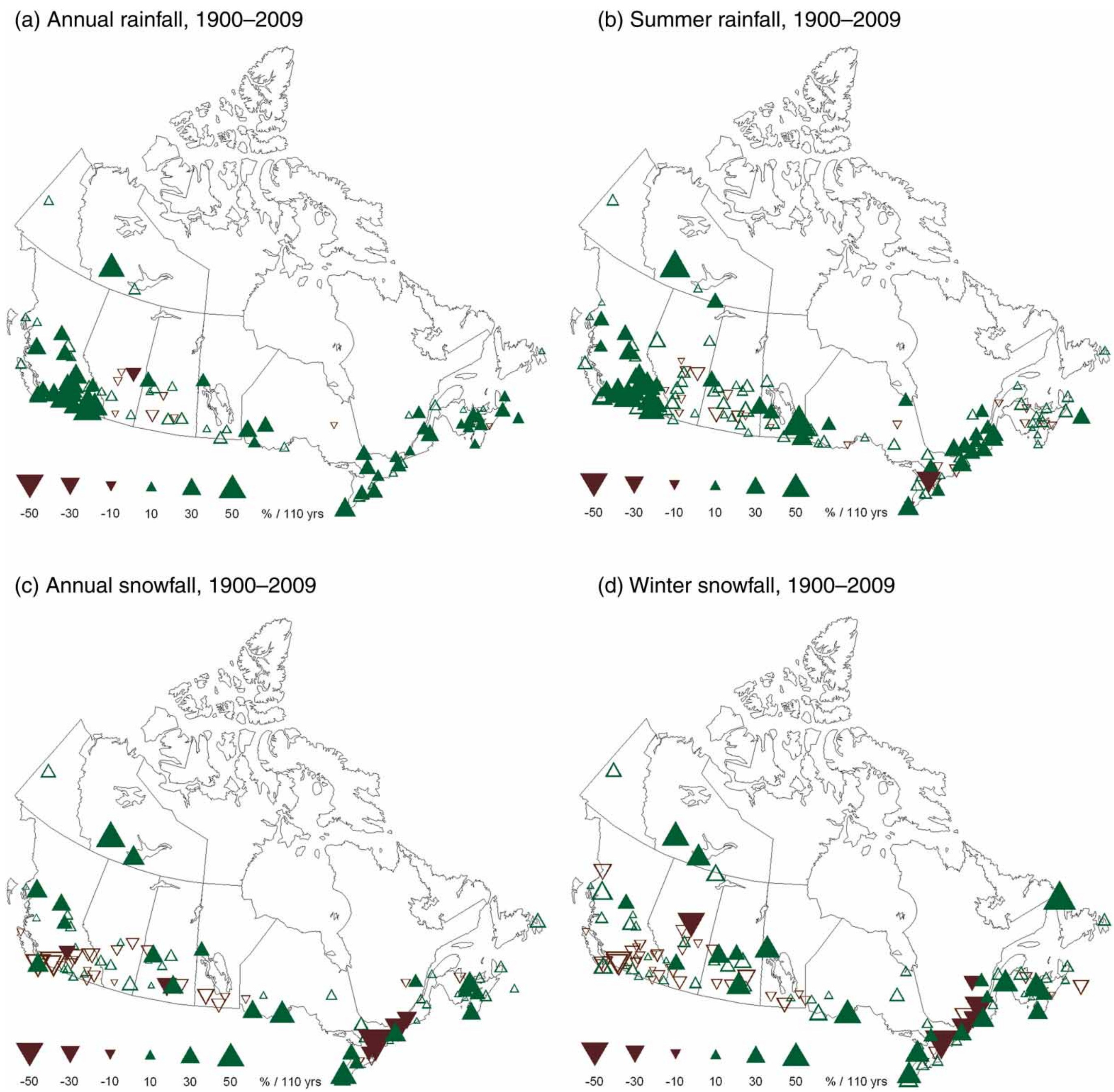

Fig. 12 Trends in annual and seasonal rainfall and snowfall for 1900–2009. Upward and downward pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

analyzed. However, because of the difficulties in the quality control of daily rainfall and snowfall for possible errors or outliers, caution should be used when daily precipitation is used in the analysis of climate indices and extremes. It is also important to note that the fresh snowfall water equivalent adjustment factor applied exhibits significant temporal and spatial variability; thus, this adjustment is not recommended for short time series or for events such as blizzards and blowing snow because of the local or short-term uncertainty involved in the computation of these events.

The ACP2-Daily dataset is now available to the scientific community as part of the Adjusted and Homogenized Canadian Climate Data (AHCCD) at http://www.ec.gc.ca/dccha-ahccd/. The list of joined stations along with their exact location can be provided upon request.

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