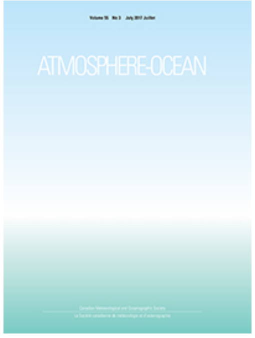

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Adjusted Daily Rainfall and Snowfall Data for Canada

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ABSTRACT *This article documents how Environment and Climate Change Canada's Adjusted Daily Rainfall and Snowfall (AdjDlyRS) dataset was developed. The adjustments include (i) conversion of ruler measurements of snowfall to its water equivalent using a previously developed snow water equivalent (SWE) ratio map for Canada; (ii) corrections for gauge-related issues including undercatch and evaporation caused by wind effects and gauge-specific wetting loss, as well as for trace precipitation amounts, using previously developed procedures for Canada. Various data flags (e.g., accumulation flags) were also treated. This dataset contains all Canadian stations reporting daily rainfall and snowfall for which we have metadata to implement the adjustments. The length of the data record varies from one station to another, starting as early as 1840. The results show that the original unadjusted total precipitation data in Environment and Climate Change Canada's digital archive underestimate the total precipitation in northeastern Canada by more than 25% and by about 10–15% in most of southern Canada. Such large underestimates make the original data unsuitable for water availability and/or balance studies or for numerical model validation, among many other applications. The use of the assumed 10:1 SWE ratio for the archived total precipitation data is the primary cause of the underestimate, which is most severe in northeastern Canada. The trace correction adds 5–20% to precipitation values in northern Canada but less than 5% in southern Canada. The gauge-related corrections do not show an organized spatial pattern but add 5–10% to the precipitation at 312 stations. Long runs (≥3 months) of miscoded missing values were also identified and corrected.*

The latest version of the AdjDlyRS dataset is available from the Canadian Open Data Portal; currently it is version 2016, which contains 3346 stations and covers the period from station inception to February 2016. This dataset is suitable for producing gridded precipitation datasets, as well as other applications.

RÉSUMÉ *[Traduit par la rédaction] Cet article décrit comment les données quotidiennes ajustées de quantités de pluie et de neige d'Environnement et Changement climatique Canada ont été créées. L'ajustement inclut i) la conversion des données de règle à neige en équivalent en eau à l'aide d'une carte existante de rapports d'équivalence neige-eau pour le Canada; ii) la correction des erreurs de captage, incluant la sous-estimation et l'évaporation dues au vent, les pertes par mouillage propre à l'instrument ainsi que la mesure de traces, et suit les procédures qui existent déjà pour le Canada. Nous avons aussi examiné divers drapeaux indicateurs (y compris celui de l'accumulation). La série contient les données relevées à toutes les stations canadiennes qui rapportent les quantités quotidiennes de pluie et de neige et pour lesquelles nous possédons les métadonnées nécessaires aux ajustements. Les séries, dont la durée varie d'une station à l'autre, commencent parfois dès 1840. Les résultats montrent que les données brutes originales de précipitations totales qu'archive numériquement Environnement et Changement climatique Canada sous-estiment les précipitations totales de 25% pour le nord-est du Canada et de 10 à 15% pour la majeure partie du sud du pays. Cette sous-estimation considérable rend les données inutilisables pour les études de disponibilité en eau, les bilans hydriques ou la validation de modèles numériques, entre autres. L'application du rapport d'équivalence neige-eau de 10:1 aux données archivées de précipitations totales s'avère la première cause de leur sous-estimation. Cette erreur est le plus prononcé pour le nord-est du Canada. La correction liée aux mesures traces augmentent de 5 à 20% la quantité de précipitations pour le nord du Canada, mais reste inférieure à 5% pour le sud. Les corrections propres à l'instrument ne sont pas spatialement organisées, mais augmentent de 5 à 10% la quantité de précipitations à 312 stations. Nous avons aussi détecté et corrigé de longues suites (≥3 mois) de valeurs manquantes mal codées.*

La dernière version de la série de données ajustées est disponible à partir du portail des données ouvertes du Canada; il s'agit de la version 2016, qui contient 3346 stations et couvre la période allant de l'activation de la

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†Hong Xu is an independent contractor who had a contract with Environment and Climate Change Canada to work on this research project, under Dr. X. L. Wang's direction, which was proposed and designed by X. L. Wang (the scientific authority of the contract).

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station jusqu'à février 2016. Ces données de précipitations peuvent être réparties sur une grille ou servir à d'autres applications.

KEYWORDS rainfall; snowfall; wind-induced undercatch; rain-gauge wetting loss; trace precipitation events; bias adjustments/correction; snowfall water equivalent

1 Introduction

Precipitation is a key variable for specifying the state of the climate system and has a high potential for impacting society and the environment. Unlike air temperature, precipitation is a non-continuous climate variable associated with an intermittent process occurring in different forms (liquid or solid, e.g., rainfall, snowfall, and ice pellets) and is highly variable both temporally and spatially (i.e., from location to location). Thus, measuring precipitation and quantifying its temporal and spatial distributions is especially challenging.

Measuring precipitation amount in a network of in situ observing stations is the conventional approach for acquiring precipitation information. Canada has had in situ observations of precipitation (using gauges and snow rulers) since 1840, with the highest number of reporting stations in the late 1980s; some locations have over 100 years of observations.

Although in situ measurements provide the most reliable precipitation observations at a specific location, station networks are often not sufficiently dense to capture all scales of precipitation, especially over the oceans, other large water bodies, and remote areas, such as northern Canada. Satellite precipitation estimates (SPEs), such as the Global Precipitation Climatology Project (GPCP) One-Degree Daily Data Set (GPCP1dd; Huffman & Bolvin, 2013; Huffman et al., 2001; Huffman, Bolvin, & Adler, 2012), may provide better representation of the spatial variation of precipitation, especially for regions with sparsely distributed observing stations (Lin & Wang, 2011) although they are derived from snapshots and not continuous accumulation over time. In situ observations are still the most accurate accumulation measurements at points although they are not continuous over horizontal space. They are of critical importance for verification, calibration, and evaluation of SPEs. Furthermore, for regions with sparse in situ observations, integrating SPEs with in situ data is the most promising way to generate high quality gridded precipitation data, making the best use of observational data from different observing systems (Lin & Wang, 2011). However, the quality of the resulting blended precipitation data largely depends on the quality of the in situ precipitation data used in the blending; while a high quality gridded precipitation dataset is especially important for the evaluation of simulations by numerical weather prediction and climate models, as well as for water availability studies and hydrological modelling.

Despite the previous discussion, the in situ data are not necessarily the ground truth data because of technical difficulties and losses associated with measuring instruments and procedures. Therefore, in situ rainfall and snowfall data often need to be corrected for systematic measuring errors (Chvila, Sevruk, & Ondrás, 2005; Goodison, Louie, & Yang, 1998; Larson & Peck, 1974; Legates & Willmott, 1990; Sevruk, 1989; Ungersböck, Rubel, Fuchs, & Rodolf, 2001; Yang, Kane, Zhang, Legates, & Goodison, 2005). Great efforts have been made to adjust daily precipitation data in Canada, especially for the detection of historical trends in precipitation. Mekis and Hogg (1999) developed the first generation of the adjusted daily precipitation dataset for 469 stations in Canada for trend analysis (stations that were selected as the best long-term stations at that time, with observations from 23 stations being joined with observations from nearby stations to create long records of precipitation data for trend analysis). Mekis and Vincent (2011) produced the second generation of this dataset with a new snow water equivalent (SWE) ratio map (Mekis & Brown, 2010), which includes more long-term stations and some other improvements. However, these datasets included only 463 stations, with observations from 234 stations being joined with observations from nearby stations to create long records of precipitation data for trend analysis (the joined series were tested for temporal homogeneity; see Mekis & Vincent, 2011). A large number (>2500) of stations with shorter precipitation records were not included or adjusted, primarily because these stations did not have data for the baseline period 1961–1990 needed to define the baseline climate for computing anomalies for monitoring purposes. However, the data from these stations are of critical importance in representing the spatial distribution and variability of precipitation; some of these stations now have a data record as long as some of those in the original dataset of 463 stations (798 stations before joining of stations; these stations were chosen by Mekis and Hogg (1999) in the late 1990s).

This paper documents the development of the Adjusted Daily Rainfall and Snowfall (AdjDlyRS) dataset that includes all stations with daily rainfall and snowfall data for which we have metadata to do the adjustments, regardless of the record length. The current version (version 2016) of this dataset covers a total of 3346 stations, including all 798 stations that were previously used by Mekis and Vincent (2011) to form the set of 463 long-term stations. This dataset is suitable for producing gridded precipitation datasets, including precipitation reanalysis, such as the Canadian Precipitation Analysis (CaPA) of Lespinas, Fortin, Roy, Rasmussen, and Stadnyk (2015). However, long-term records in this dataset are also suitable for climate change studies, and more long-term records could be formed in the future for climate change studies by joining some of these stations using a data homogenization procedure.

A few years ago, in order to meet the demand for adjusted daily rainfall and snowfall data, we released an interim version (version 2007) of the AdjDlyRS dataset, which contained

2146 stations and covered the period from 1840 or later to 2007. Version 2007 was used to produce the first gridded blended pentad precipitation dataset (Lin & Wang, 2011); it was available from the Canadian Open Data Portal and has now been replaced by version 2016 on the Open Data Portal (http://open.canada.ca/data/en/dataset/d8616c52-a812-44ad-8754-7bcc0d8de305). We developed both versions (2007 and 2016) of the dataset in exactly the same way; the only difference is that more stations were added in version 2016. This article is intended to be the reference for all versions of the AdjDlyRS dataset (including future versions).

The remainder of this article is arranged as follows. Section 2 provides some Canadian precipitation measurement history and data background information. All adjustment and correction procedures are detailed in Section 3. The effects of the various adjustments are quantified and discussed in Section 4. The identification and correction of long runs of miscoded missing values is described in Section 5. Section 6 completes this article with some concluding remarks.

2 Canadian precipitation measurement history and the archived daily rainfall and snowfall data

The method used in Canada to measure rain has changed several times. The most important of these are changes to the type of rain gauges used. The current official manual rain gauge is called the Type-B, which was introduced at most locations across Canada during the 1970s. The Meteorological Service of Canada (MSC) gauge (also called the Type-A gauge) was used before the Type-B gauge was adopted. The MSC gauge was originally manufactured entirely from copper (MSC copper), but the inside container was modified to a soft plastic material with different wetting characteristics (MSC plastic) around 1965. A more complete description of these gauges can be found in Metcalfe, Routledge, and Devine (1997) and Devine and Mekis (2008).

The depth of freshly fallen snow, measured by ruler, has been the standard measurement of snowfall since the 1840s. For all stations prior to the 1960s and for non-synoptic stations over the entire record, precipitation amount (as SWE) for a snowfall event has been archived by assuming a fresh snow density of 100 kg m^{-3} (Mekis & Brown, 2010), namely, a SWE ratio of 10:1 (i.e., 10 mm of snowfall equals 1 mm of rainfall). When the Nipher-shielded snow gauges were introduced at nearly 300 synoptic stations in the early 1960s, direct measurements of SWE became available. However, because of the greater longevity of ruler measurements and higher station density at which they are made, which provides better spatial coverage, snowfall data from ruler measurements are of crucial importance. Also, the estimate of fresh snow density can be improved because of the availability of coincident Nipher gauge and snow ruler measurements since the 1960s (Metcalfe, Ishida, & Goodison, 1994). This study used snowfall ruler measurements to produce the AdjDlyRS dataset. The concurrent Nipher gauge data were used in developing the SWE adjustment factor map (Mekis & Brown, 2010), which was also used in this study.

In Canada, station automation started generally in the 1990s, with more and more stations being automated in the past decade or so. The majority of the stations in the North (north of 60°N) are automatic stations. However, measurements by automatic systems were not included in this study because the method for correcting and adjusting automated precipitation measurements is still under development, and work on this will be reported in a separate study by our colleagues.

Daily rainfall gauge and snowfall ruler data were extracted directly from the National Climate Data Archive of Environment and Climate Change Canada (ECCC). All rainfall and snowfall measurements used in this study (the AdjDlyRS dataset) were made by human observers. Following Mekis and Hogg (1999) and Mekis and Vincent (2011), we adjusted rainfall and snowfall separately, which facilitates the correction of known problems, such as instrument deficiencies and changes in observing procedures.

Station history files were searched for metadata information, for example, gauge-related information, such as installation dates of rain gauges, and measurement procedure changes, such as the introduction date of the 6-hourly and hourly measurement program, as well as dates of station closure and/or relocation. Metadata information was also provided by national experts in climate observing and climate practices. These precipitation-related metadata are critical when producing the AdjDlyRS dataset.

Limited by the availability of precipitation metadata at the time of this work, a total of 3346 stations (Fig. 1) are included in the AdjDlyRS dataset, version 2016. Although more stations are located in southern Canada (south of 55°N), a number of stations can be found in northern Canada (north of 55°N) where climate and meteorological stations are generally sparse. As shown in Fig. 1, the data record length is more than 60 years at 403 stations (most of them in the South), 41–60 years at 505 stations, and 21–40 years at 975 stations. Not surprisingly, the number of available stations changes over time, as shown in Fig. 2. The number of stations in the 1948–1964 and 1965–2008 periods ranged from 512 to 958 and from 1012 to 2038, respectively; after 2008 the number of stations ranged from 398 to 887. The significant reduction in the number of stations after 2008 is, in part, due to station automation because precipitation data from automated stations are not included in this study. Also, there is generally a delay (up to about two years) for the data from volunteer stations to enter the archive, which is the reason for the particularly low numbers of stations for the most recent two years (Fig. 2).

3 Corrections and adjustments

Four major procedures were applied to the archived daily rainfall and snowfall data to produce the AdjDlyRS dataset (all versions). These include (i) conversion of snowfall ruler measurements to their water equivalent amounts using the

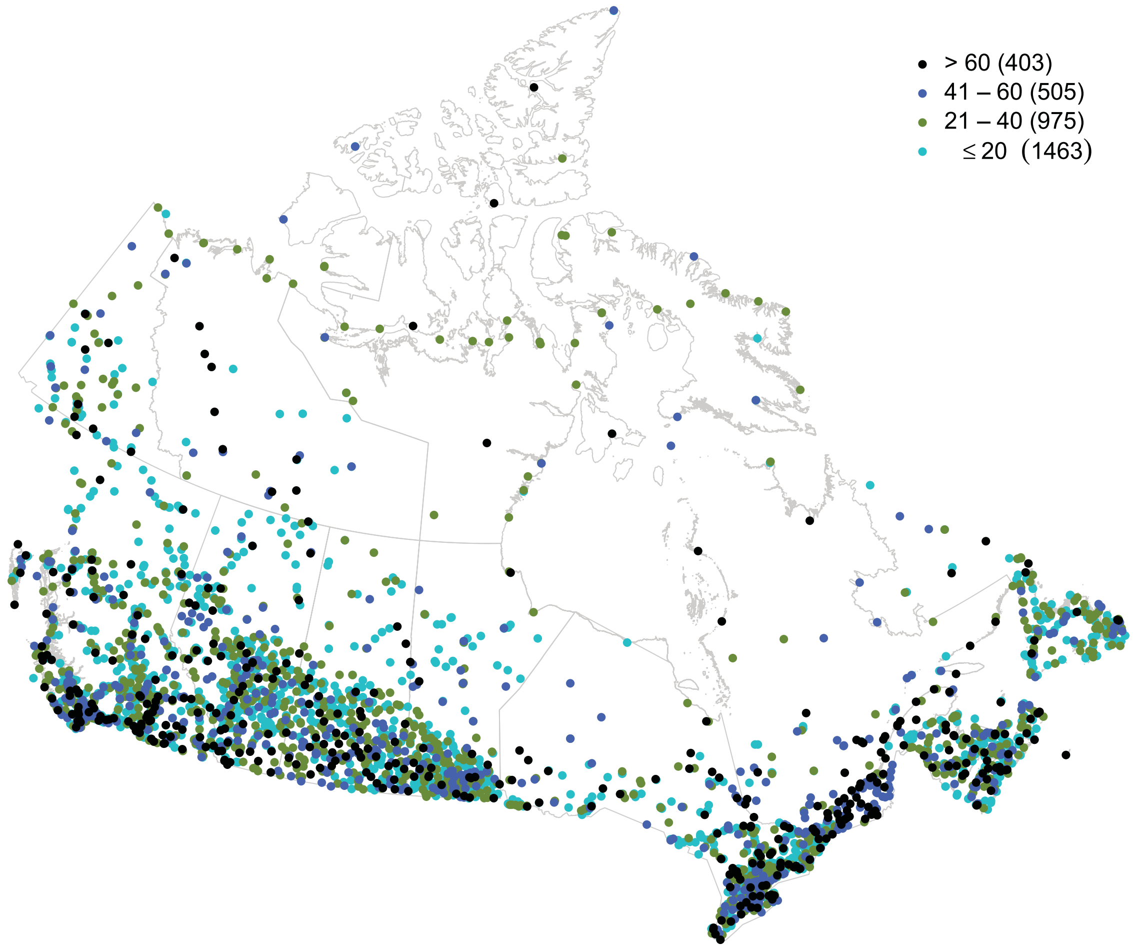

Fig. 1 Locations and record lengths of the 3346 stations included in the Adjusted Daily Rainfall and Snowfall (AdjDlyRS) dataset version 2016. The coloured dots indicate record length (years). The number of stations with the indicated record length is shown in parentheses in the legend.

SWE ratio map for Canada developed by Mekis and Brown (2010); (ii) corrections for gauge undercatch and evaporation due to wind effect, for gauge-specific wetting loss, using the methods detailed in Mekis and Hogg (1999), Devine and Mekis (2008), and Mekis and Vincent (2011); (iii) assignment of a small precipitation amount to days with a trace flag (Mekis & Vincent, 2011); and (iv) adjustment of daily precipitation data for flags other than trace (e.g., accumulation flags C, L, A, and F) following the procedure used in Hutchinson et al. (2009). More details about these procedures are given in the following subsections.

a *Conversion of snowfall ruler measurements to water equivalents*

The ECCC archive includes daily rainfall, daily snowfall, and daily total precipitation, which is the sum of daily rainfall and daily SWE from snowfall. Daily ruler measurements of snowfall were automatically converted to daily SWE in the archive using a conversion ratio of 10:1, that is, 10 mm of snowfall is assumed to be equivalent to 1 mm of rainfall. However, the 10:1 ratio has proven inaccurate based on studies using the coincident Nipher gauge and snow ruler measurements in Canada since the 1960s (Mekis & Brown, 2010; Metcalfe et al., 1994).

In order to estimate the SWE ratios across Canada, Mekis and Brown (2010) developed a map of SWE adjustment factors (ρ_{SWE}) for Canada using 175 climatological stations with more than 20 years of concurrent ruler and Nipher gauge observations. The adjustment factors ρ_{SWE} were evaluated using independent data and show a spatial pattern consistent with processes influencing the density of fresh snowfall and its initial settling (Mekis & Vincent, 2011). An older version of the ρ_{SWE} map based on fewer overlapping snow ruler and Nipher locations was originally applied to the first-generation adjusted daily precipitation dataset for trend analysis in Canada (Mekis & Hogg, 1999). The new calculation is based on corrected solid Nipher gauge precipitation to snowfall ruler measurement ratios when both were operational.

In this study, we adopted the latest version of the ρ_{SWE} map as used in Mekis and Vincent (2011), which was developed by Mekis and Brown (2010). That is, we applied the SWE adjustment factor ρ_{SWE} to adjust all snowfall ruler measurements, which is equivalent to replacing the 10:1 ratio with the 10:ρ_{SWE} ratios. The values of ρ_{SWE} range from more than

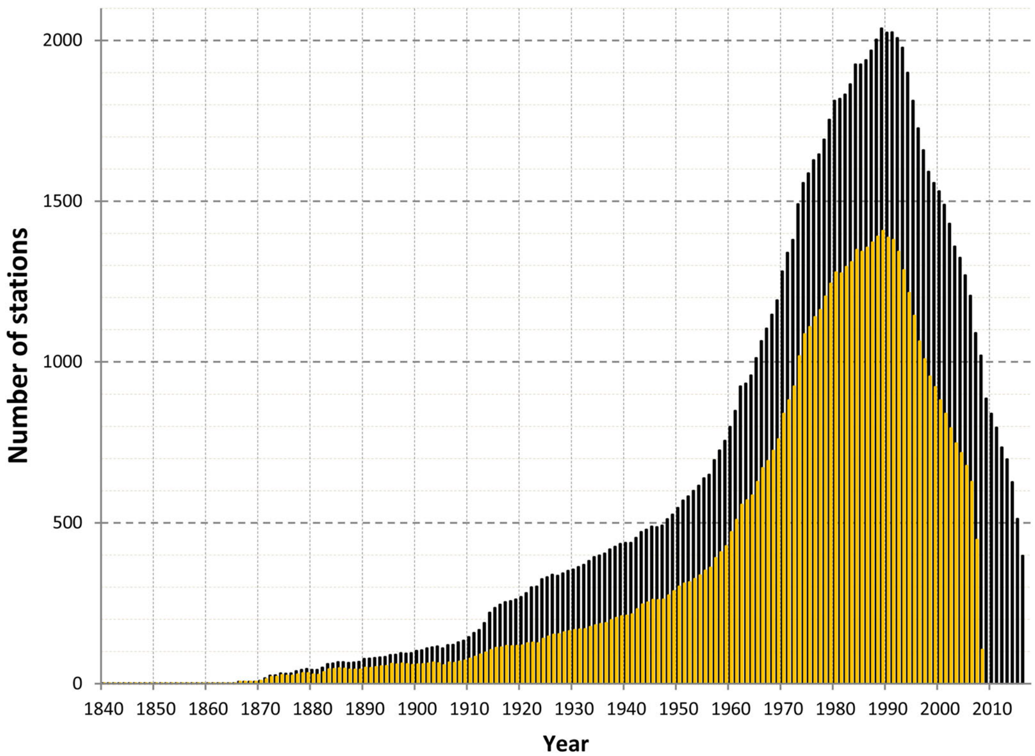

Fig. 2 Number of stations each year with observed data in the Adjusted Daily Rainfall and Snowfall (AdjDlyRS) dataset version 2016 (black) and version 2007 (orange).

1.5 in the Maritimes to less than 0.8 in south central British Columbia (see Fig. 2 of Mekis & Vincent, 2011) and are greater than one for most areas of Canada. Thus, the use of the assumed 10:1 ratio resulted in substantial underestimation of precipitation amount (SWE) in most areas in Canada (see below).

b *Rain-gauge specific corrections*

Different rain gauges behave differently because of several factors, such as wind effects and wetting loss. An intercomparison study on rain gauges conducted by Environment Canada (i.e., now ECCC) reported systematic differences between the MSC gauge and a pit gauge (gauge with an orifice at ground level; therefore, wind speed is at a minimum) to be about 4% (Goodison & Louie, 1986). Both MSC and Type-B gauges are mounted relatively low to the ground to reduce the undercatch due to wind. The systematic difference between the Type-B gauge and a pit gauge is less than 2% at an open, windy site. The wetting loss has two known components after a precipitation event: the water subject to evaporation from the surface of the funnel and the inner walls of the precipitation gauge before emptying, and the water retained on the walls of the gauge and on the funnel after emptying (Metcalfe et al., 1997; Routledge, 1997). The MSC copper and plastic inserts have different wetting loss characteristics, as is also the case for the all-plastic Type-B gauge with its different thermal characteristics and direct-reading design.

For daily rainfall data, we applied the gauge-specific adjustments proposed in Mekis and Vincent (2011), which were a refinement of those in Mekis and Hogg (1999) and based on more field experiments performed at various locations (Devine & Mekis, 2008). Adjustments for rain-gauge specific corrections were applied using the following equation from Devine and Mekis (2008):

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

where R_a is the adjusted daily rainfall (millimetres), R_m is the measured daily rainfall (millimetres), F_c is the funnel wetting correction (millimetres), E_c is the evaporation from container correction (millimetres), C_c is the container/receiver retention correction (millimetres), and W_c is the wind correction factor. The same values of $(F_c + E_c + C_c)$ and W_c listed in Table 1 of Mekis and Vincent (2011) were applied in this study, namely, $(F_c + E_c + C_c) = 0.21$, 0.19, and 0.13 mm for MSC copper receivers, MSC plastic receivers, and Type-B gauges, respectively, and $W_c = 4\%$ and 2% for MSC receivers and Type-B gauges, respectively.

It is sometimes difficult to determine rain-gauge types because of incomplete metadata; rain-gauge information may be unclear or not consistently recorded for all stations. To enable gauge-specific adjustments for a large set of stations, we applied the following general rules to determine the rain-gauge type in use at the time:

TABLE 1. The 30-year (1971–2000) average of total adjustments to the cold season (October–March), warm season (April–September), and annual precipitation totals averaged across all stations in northern and southern Canada and across all stations in four regions: British Columbia (BC), the Prairies (Alberta, Saskatchewan, and Manitoba), Ontario (ON), and southeastern Canada (SE).

	Cold Season	Warm Season	Annual	Cold Season	Warm Season	Annual
Northern Canada (North of 55°N)				*Southern Canada (South of 55°N)*		
Change (mm)	19.6	24.1	43.7	40.5	24.3	64.8
% change	10.6	9.2	9.8	8.1	5.5	6.9
British Columbia (BC)				*Prairies*		
Change (mm)	15.0	20.5	35.5	18.8	19.5	38.3
% change	1.7	5.0	2.7	14.5	5.8	8.2
Ontario (ON)				*Southeastern Canada (SE)*		
Change (mm)	42.8	24.5	67.3	104.1	35.7	139.8
% change	10.0	5.0	7.3	16.6	6.1	11.6

- Unless there are clear indications of other types of rain gauges, corrections to the MSC copper gauge were applied to daily rainfalls reported up to 31 December 1964.
- Corrections for the MSC plastic liner (Type-A) gauge were applied to daily rainfall for the time period from the documented installation date of the MSC plastic gauge to the documented installation date of the Type-B gauge. If the installation date of the MSC plastic gauge was not documented or if "standard," "ordinary," and "unknown" were documented in the metadata, corrections for the MSC plastic liner rain gauge were applied to the data from 1 January 1965 onwards (this happened at 2.64% of stations).
- Corrections for Type-B gauges were applied to daily rainfall from the documented installation date of the Type-B gauge to the end of the record, unless another type of rain gauge was identified from the metadata.

c *Trace precipitation*

A trace precipitation event refers to the occurrence of precipitation below the smallest measurable amount and is conventionally recorded as zero. Trace precipitation events are frequent in Canada, especially in the Canadian Arctic, where assigning a small precipitation amount to each trace event may increase the annual total precipitation by up to 20% (Mekis, 2005). Therefore, estimating precipitation amounts from trace precipitation events is critical for Canada.

Trace precipitation events include both trace rainfall and trace snowfall events, for which different methods of adjustment were used. According to Mekis and Hogg (1999), for both trace rainfall and trace snowfall events, the trace adjustment factor depends on the number of observations per day. The most time-consuming part of the trace correction procedure is identifying the number of precipitation observations per day at each station and determining from metadata how this number changed over time. Adjustments for the frequency of trace precipitation events were applied only to stations with more than one observation per day ranging from two to four (including any combination).

For rainfall trace correction, because the amounts between 0.0 and 0.2 mm were considered equally probable, the average of 0.1 mm was applied for all stations (Mekis & Hogg, 1999). Following Mekis and Hogg (1999), the daily trace rainfall amount R_{trace} (millimetres) was estimated using the trace occurrence ratio for x-hour observation interval, $T_{or,x}$, as follows:

$$\begin{aligned} R_{trace} &= 0.1T_{or,12}, \\ &\quad \text{where } T_{or,12} = 1.50, \text{ for two observations per day;} \\ R_{trace} &= 0.1T_{or,8}, \\ &\quad \text{where } T_{or,8} = 2.25, \text{ for three observations per day;} \\ R_{trace} &= 0.1T_{or,6}, \\ &\quad \text{where } T_{or,6} = 3.00, \text{ for four observations per day.} \end{aligned} \quad (2)$$

Solid trace precipitation often occurs as ice crystals when air temperature is very low, especially at high latitudes, and ice crystals usually contain little water. Thus, the ice crystal ratio (ICR), which is the ratio of ice crystal events to the total snowfall trace events, is also needed to assign a specific amount to a solid precipitation trace event. Following Mekis and Hogg (1999), the daily adjustments for solid precipitation trace events were estimated as follows:

$$\begin{aligned} S_{trace} &= I_{trace}T_{or,12}, \\ &\quad \text{where } T_{or,12} = 1.50, \text{ for two observations per day;} \\ S_{trace} &= I_{trace}T_{or,8}, \\ &\quad \text{where } T_{or,8} = 2.25, \text{ for three observations per day;} \\ S_{trace} &= I_{trace}T_{or,6}, \\ &\quad \text{where } T_{or,6} = 3.00, \text{ for four observations per day;} \end{aligned} \quad (3)$$

where $I_{trace} = 0.07 - (\text{ICR} - 40\%)\,(0.07 - 0.03)/(70\% - 40\%)$, for ICR > 40% events; $I_{trace} = 0.07$, for ICR ≤ 40% events.

The ICR increases towards higher latitudes. The ICR value for each station was obtained from the map published as Fig. 3 of Mekis and Hogg (1999), which was derived from the frequency ratio of the number of ice crystal events to the number of solid precipitation trace events based on hourly weather data.

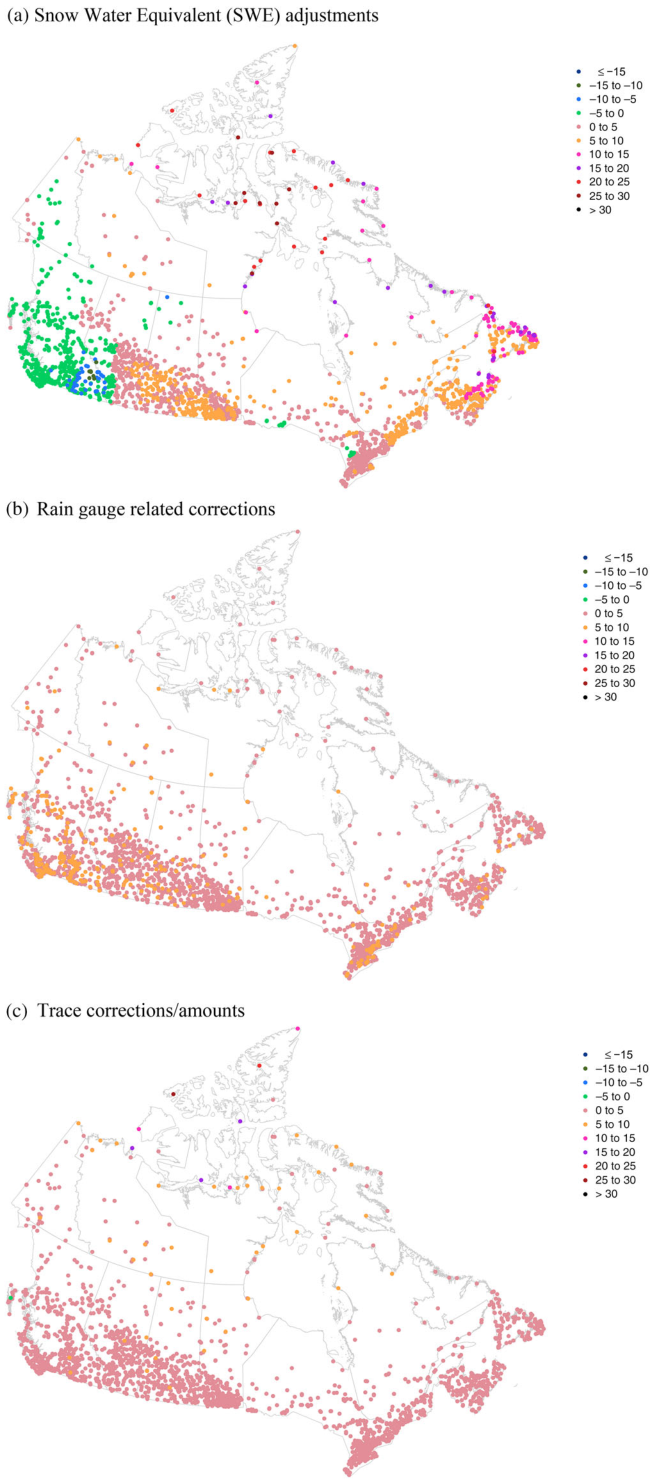

Fig. 3 Long-term mean amounts of the indicated adjustments and/or corrections applied to the annual total precipitation, expressed as a percentage of the long-term mean of the corresponding original unadjusted annual total precipitation.

d *Adjustments for other reported flags*

Except for the trace flag (which was treated as described in Section 3.c), all other flags reported in both daily rain-gauge data and snowfall ruler measurements were treated using the method described in Hutchinson et al. (2009), which is summarized below. In total, 0.94% of the data were affected.

Here, the focus was mainly on the accumulation flags, including (i) the C flag, which indicates "precipitation occurred, amount uncertain with a reported value 0"; (ii) the L flag, which indicates "precipitation may or may not have occurred with a reported value 0"; (iii) the A flag, which indicates "accumulated amount with a previous flag C or L"; (iv) the F flag, which indicates "accumulated and estimated values"; (v) the E flag, which indicates estimated values and was treated the same way as values with no flags for the purposes of this study, accepting the estimated values that were in the archive; and (vi) the M flag, which indicates missing values and was treated as missing with no values assigned (Environment and Climate Change Canada, 2017).

The principles used to treat these accumulation flags are as the follows.

- *A value with a C or L flag followed by a non-zero value with a blank or E flag*. In this case, it was apparent that the A flag was omitted in the case of a blank flag or incorrectly assigned in the case of an E flag. Thus, an A flag was inserted in place of the blank or E flag for subsequent processing.
- *A value or series of values with C and/or L flags followed by a missing value*. There is no way to reconcile a missing value for C or L flags. Therefore, all values with a C or L flag leading up to the missing value were likewise set to missing.
- *A value with a C or L flag followed by a zero value and a blank flag*. Again, the C and L flags are incompatible with a zero and a blank flag by definition. Thus, the values with a C flag or an L flag were set to missing. Occasionally there was an A or F flag not preceded by a C flag or an L flag. In those cases, the value with the A or F flag was set to missing.
- *The typical entry in the archive is 0C (value 0, flag C) on one day followed by a non-zero value with an A flag on the next*. However, there can be a series of 0C and/or 0L (value 0, flag L) values followed by a non-zero value with either an A or an F flag. Events longer than four days were set to missing.

For all situations with accumulation flags other than the cases mentioned above, the following method was applied. It was assumed that the distribution of precipitation over the accumulation period could be estimated from the distribution of precipitation at neighbouring stations within a 100 km radius over the same period. The total precipitation at each of the neighbouring stations was determined for the accumulation period and then the daily amounts expressed as a fraction of the total. An inverse squared distance weighting scheme was employed to emphasize the closest station and to give lesser weight to those further away. If precipitation at a neighbouring station was also accompanied by a flag (except an E flag), this station was not used for this purpose. If there were no neighbouring stations with valid data within the 100 km radius, then values for all the days in the accumulated event were set to missing. In total, days associated with an accumulated amount that were set to missing, including the events that were longer than four days mentioned earlier, account for 0.081%; however, these accumulated values were retained for calculating the monthly total precipitation.

4 Effects of the adjustments

The adjustments applied to daily rainfall and snowfall data could result in changes in the long-term mean values and spatial patterns of precipitation. Generally speaking, with the exception of the SWE adjustments, all other adjustments will increase the total precipitation amounts. However, because the SWE adjustment factor ρ_{SWE} ranges from smaller than 0.8 in British Columbia to larger than 1.5 in the Maritimes, the final adjusted precipitation totals could be reduced in regions where $\rho_{\mathrm{SWE}} < 1.0$. In this section, we assess the changes due to each adjustment.

a *Relative effects of different adjustments on annual total precipitation*

For each of the stations with at least five years of data, we calculated the differences between the long-term mean (the mean over the full data period of record) of total precipitation derived from the adjusted data after each of the three types of procedures (SWE adjustments, rain-gauge-related corrections, and trace corrections) and from the unadjusted data (treatment of all other flags made small changes in long-term mean annual precipitation totals, which is not shown). These differences are the long-term mean amounts of the indicated adjustments applied to the annual total precipitation, which were expressed as a percentage of the long-term mean of the corresponding unadjusted annual total precipitation and shown in Fig. 3.

Not surprisingly, the pattern of changes resulting from the SWE adjustments (Fig. 3a) is similar to the spatial distribution of the SWE adjustment factor ρ_{SWE} shown in Fig. 2 of Mekis and Vincent (2011). The SWE adjustments increased the annual precipitation totals for most regions across Canada, showing increases of over 25% in northern Canada and up to 10% in most areas of southern Canada, while small decreases of a few percent are seen in British Columbia and Yukon.

Applying the rain-gauge-related corrections resulted in an increase of mostly 5–10% in mean annual precipitation totals at all stations (Fig. 3b). The trace corrections also

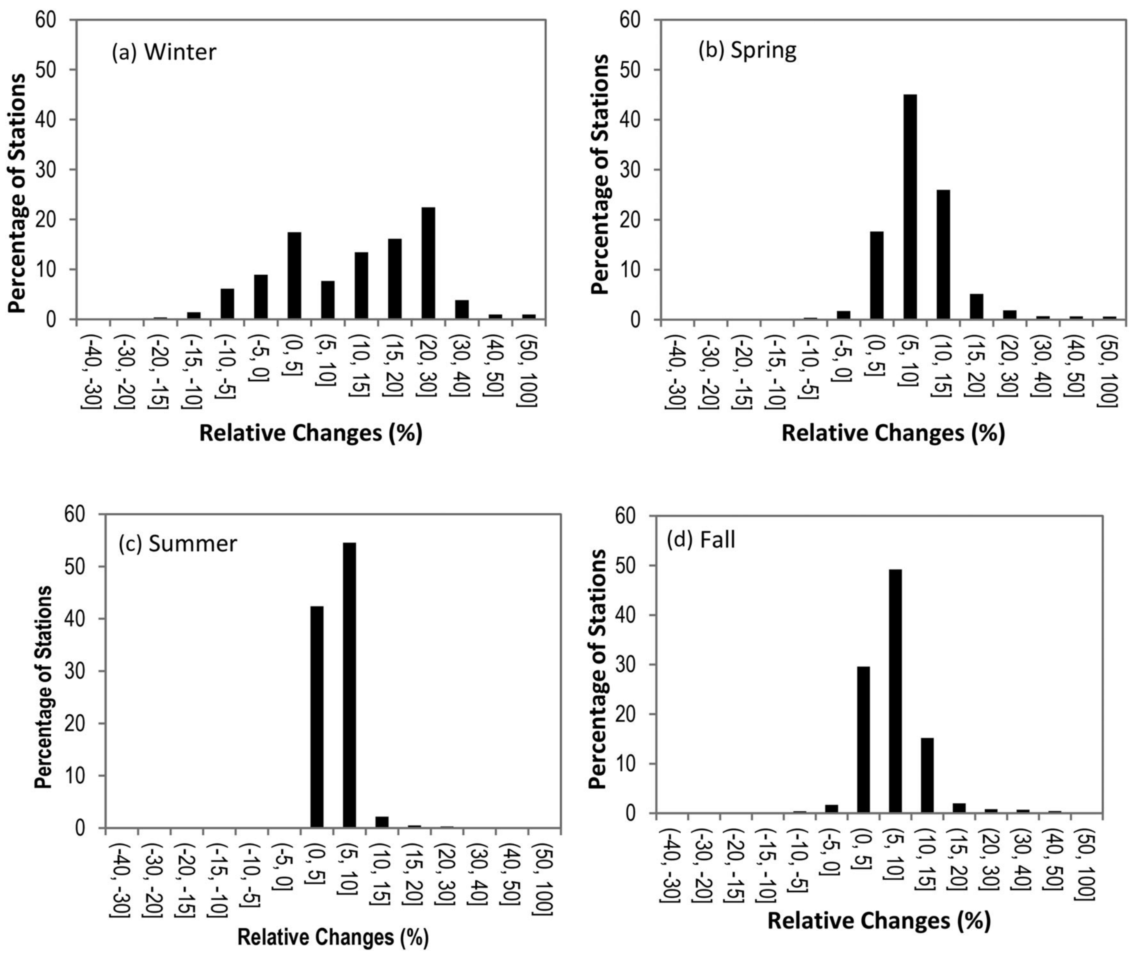

Fig. 4 Percentage of stations having different categories of relative changes in seasonal precipitation totals after applying all the adjustments for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) fall (SON). The relative changes are given as a percentage of the long-term mean of the corresponding unadjusted precipitation.

increased the annual precipitation totals at all stations, showing increases of 5–30% in the Canadian Arctic and increases of less than 1% for the other stations (Fig. 3c). The larger percentage changes in the Arctic are, in part, a result of the small annual precipitation totals there.

The total adjustments show seasonality. Figure 4 shows the percentage of stations having different categories of relative changes due to all the adjustments applied to winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November) precipitation totals. The total adjustments resulted in large increases in winter precipitation totals (Fig. 4a), with about 17, 8, 13, 16, and 22% of the stations showing below 5%, 5–10%, 10–15%, 15–20%, and 20–30% increases, respectively; and about 9 and 6% of the stations showing decreases below 5% and 5–10%, respectively. The total adjustments had much smaller effects on summer precipitation totals (Fig. 4c), with 42 and 52% of the stations showing increases below 5% and 5–10%, respectively. This is because snowfall may occur only occasionally in the North in summer. In the transition seasons (Figs 4b and 4d), the effects are somewhat similar to those in summer but with many more stations showing increases of more than 10% (at about 35, 19, and 3% of the stations in spring, fall, and summer, respectively).

Thus, the relative changes in annual precipitation totals resulting from the adjustments are much smaller than those in the winter precipitation totals, with about 27, 43, and 22% of the stations showing below 5%, 5–10%, and 10–15% increases in annual precipitation totals (not shown).

b *Relative effects of total adjustments on snowfall totals and rainfall totals*

Because the adjustment procedures were applied to daily snowfall and rainfall separately, the effect of the total adjustments on annual snowfall totals and rainfall totals is different. Figure 5 shows the long-term mean of the total adjustments applied to the annual snowfall, rainfall, and total precipitation, expressed as a percentage of the long-term mean of the corresponding unadjusted snowfall, rainfall, and total precipitation, respectively.

As shown in Fig. 5, the relative changes in snowfall (in terms of water equivalent), are usually much larger than those in rainfall. The relative changes in snowfall show a spatial pattern (Fig. 5a) following the pattern of the SWE adjustment factor map (Fig. 2 of Mekis & Vincent, 2011); snowfall totals show a decrease when the SWE adjustment factor is smaller than unity and an increase when the factor is greater than unity. In contrast, the total adjustments resulted in an increase in rainfall totals at all stations, and the relative increases are often smaller than 10%, except in regions, such as northern Canada, where annual rainfall totals are relatively small (Fig. 5b). For the long-term mean annual total precipitation, the adjustments for rain-gauge-related losses and trace events partly compensated for the reductions introduced by the SWE adjustment in regions where $\rho_{swe} < 1$ (British Columbia and Yukon). Thus, the overall effects of the total adjustments on annual total precipitation are increases

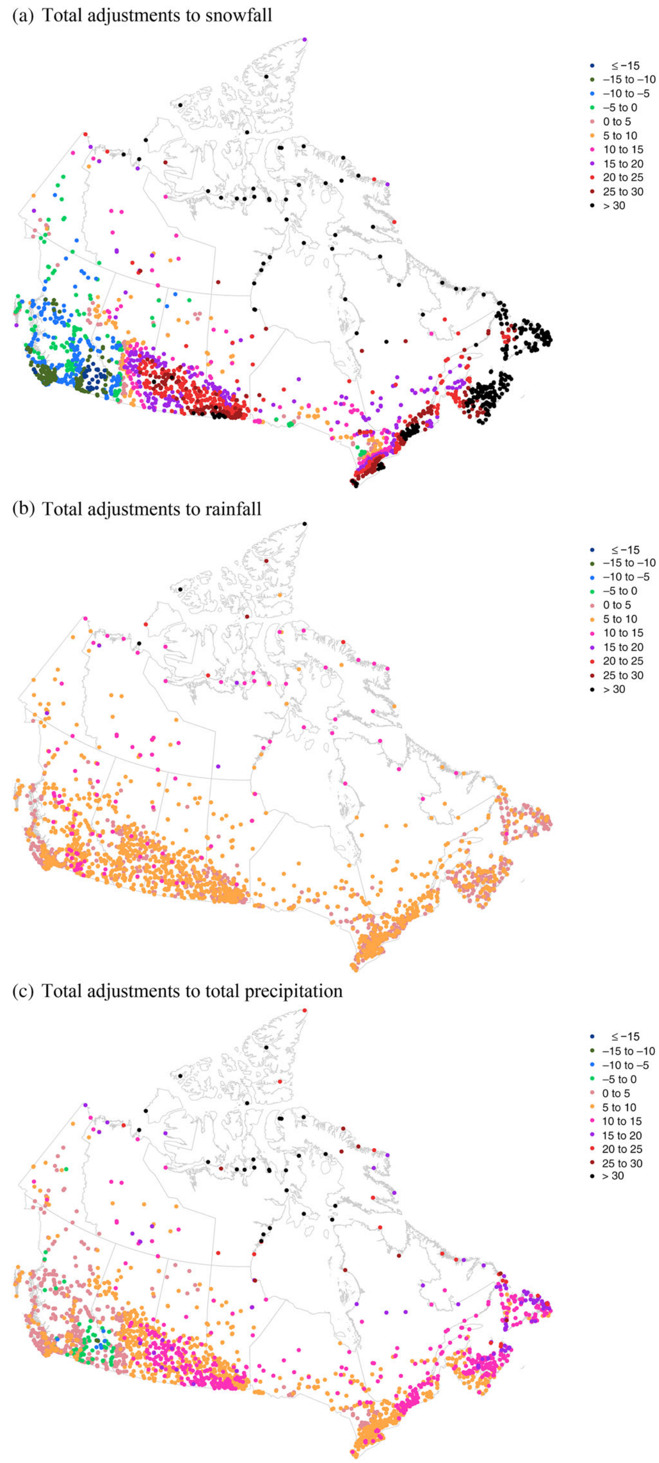

Fig. 5 Long-term mean of the total adjustments and/or corrections applied to the annual (a) snowfall, (b) rainfall, and (c) total precipitation, expressed as a percentage of the long-term mean of the corresponding unadjusted snowfall, rainfall, and total precipitation.

greater than 25% in northern Canada and 5–25% at most stations in southern Canada, with the exception of a few stations in British Columbia and Yukon that have decreases up to 15% (Fig. 5c).

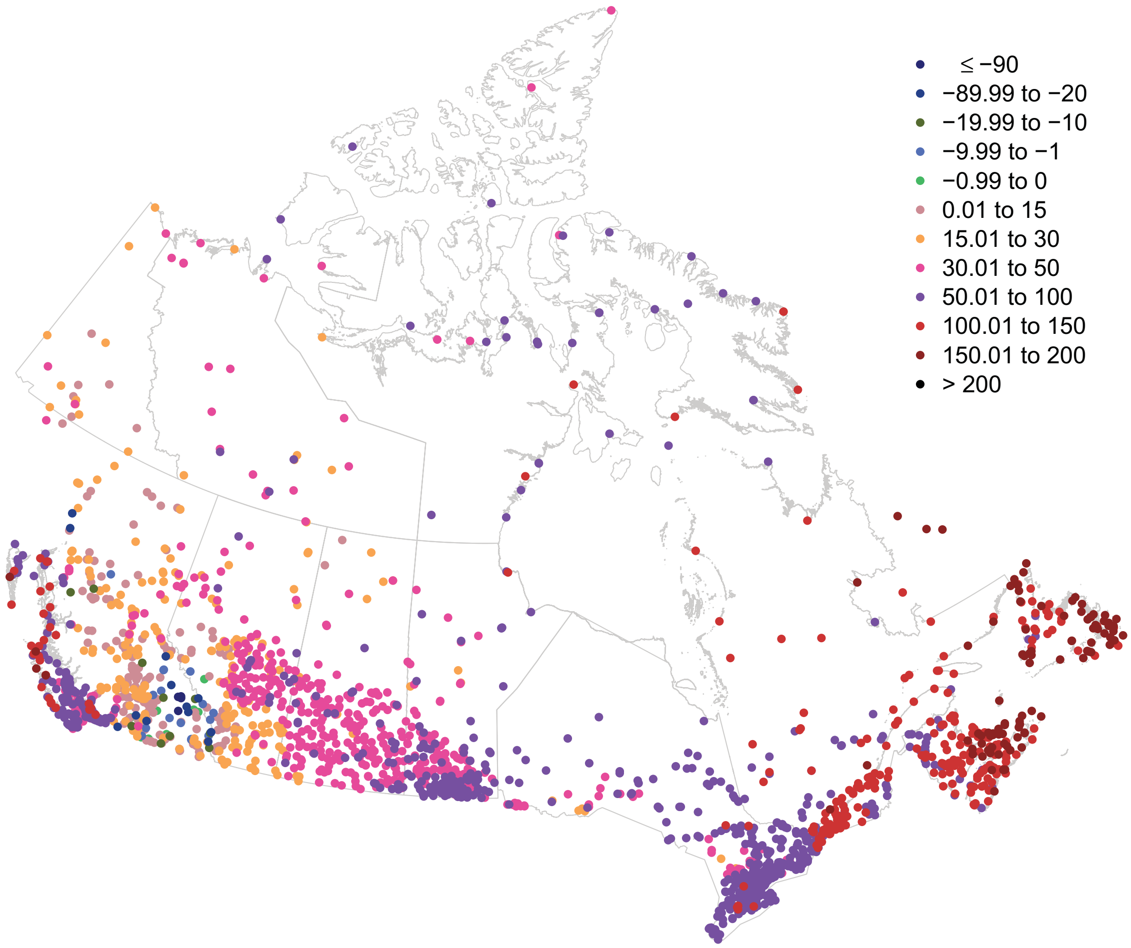

Fig. 6 Long-term mean of the total adjustments (mm) applied to the annual total precipitation.

c *The total adjustments to annual total precipitation*

Figure 6 show the long-term mean of the actual amounts of the total adjustments applied to the annual total precipitation (only stations with at least five years of data are shown here). The largest adjustments are seen on the east coast and the smallest in the Rocky Mountains (Fig. 6). The adjustments increased the climatological annual total precipitation by 100–344 mm for the majority of stations in eastern Canada, 50–100 mm for most stations in Ontario, Vancouver Island, and the coastal area of British Columbia, 30–100 mm for most stations in Manitoba and Saskatchewan, 15–50 mm for most stations in Alberta, and up to 30 mm for most stations in the Rocky Mountains, but they decreased the climatological annual total precipitation at some stations in the Rocky Mountains (Fig. 6; most decreases are smaller than 89 mm, except for stations Lardeau Creek Galena Lodge (1144582), Glacier NP Rogers Pass (1173191), Glacier (1173180), and Glacier NP Mt Fidelity (117CA90) in British Columbia which have 117, 153, 160, and 260 mm decreases, respectively).

d *Effects of total adjustments on regional average and trends*

It is of interest to see how the total adjustments might affect regional averages, especially in southern Canada (south of 55°N) compared with northern Canada (north of 55°N), knowing that the SWE adjustments could have more significant effects in the North relative to the climatological values. Several previous studies defined northern Canada as north of 60°N, but we think that 55°N is a better division in terms of station density (see Figs 1 and 6). Because the number of available stations was relatively stable from 1971 to 2000 for both southern and northern Canada (approximately 1300 and 135 stations, respectively), we calculated monthly, seasonal, cold season (October–March) and warm season (April–September) precipitation totals and regionally averaged each of these quantities across stations in southern and northern Canada (south and north of 55°N) separately and also across stations in (i) British Columbia (BC), (ii) the Prairies (Alberta, Saskatchewan, and Manitoba), (iii) Ontario (ON), and (iv) southeastern (SE) Canada (Quebec, New Brunswick, Nova Scotia, and Newfoundland).

Figure 7 shows the time series of regionally averaged cold season, warm season, and annual precipitation totals in the adjusted (solid lines) and unadjusted data (dotted lines) for the 1971–2000 period. Clearly, the adjusted precipitation totals are always larger than their unadjusted counterparts

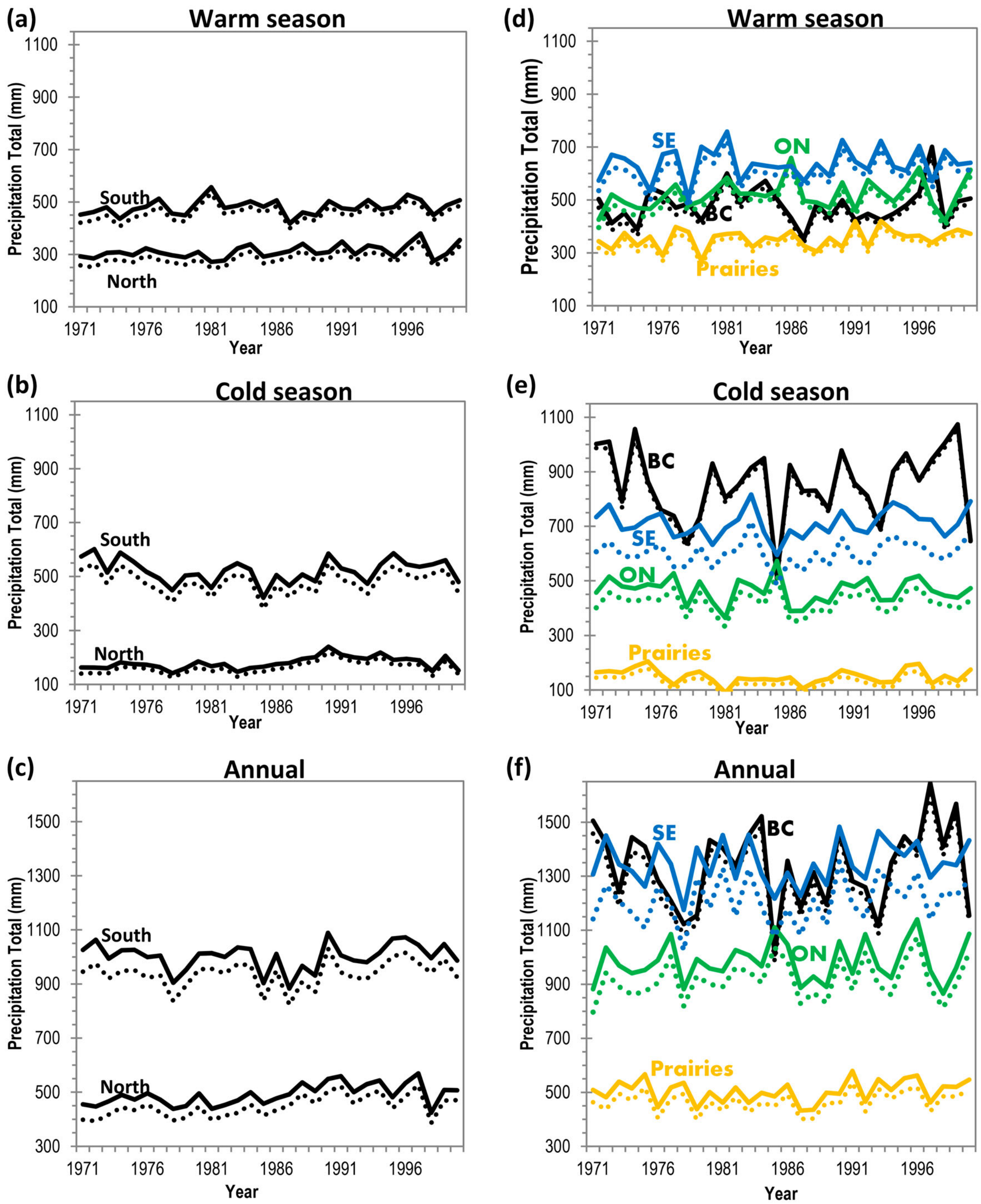

Fig. 7 Regionally averaged (a) and (d) warm season (April–September), (b) and (e) cold season (October–March), and (c) and (f) annual precipitation totals in the adjusted (solid lines) and raw (dotted lines) data for the regions south and north of 55°N, and for British Columbia (BC; black), Alberta, Saskatchewan, and Manitoba (Prairies; yellow), Ontario (ON; green), and southeastern Canada (SE; blue–Quebec, New Brunswick, Nova Scotia, Newfoundland).

for every year during this period for both cold and warm seasons and for all six regions. As shown in Table 1, the 30-year average increase resulting from the adjustments is larger in southern Canada than in northern Canada, especially for the cold season; but the relative change (percentage change) is always larger in northern Canada than in southern Canada because precipitation totals are smaller in northern Canada (Figs 7a to 7c).

In the cold season, the effect of the adjustments also varies greatly across southern Canada, with the largest relative change seen in southeastern Canada and the Prairies, and the smallest change in British Columbia (Table 1 and Fig. 7d). In the warm season, the effect does not vary much across southern Canada, showing 5.0–6.1% increases (Table 1 and Fig. 7f).

Increases in the adjusted data do not seem to notably alter year-to-year variations in the regional averages. We used a

TABLE 2. The 1971–2000 trends (mm y^{-1}) in the cold season (October–March), warm season (April–September), and annual unadjusted and adjusted precipitation totals, averaged across all stations in northern and southern Canada and across all stations in four regions: British Columbia (BC), the Prairies (Alberta, Saskatchewan, and Manitoba), Ontario (ON), and southeastern Canada (SE).

	Cold Season	Warm Season	Annual	Cold Season	Warm Season	Annual
Northern Canada (North of 55°N)				*Southern Canada (South of 55°N)*		
Unadjusted	1.54*	1.15	3.18*	1.24	0.97	1.53
Adjusted	1.56*	0.81	3.05*	1.39	0.57	0.95
British Columbia (BC)				*Prairies*		
Unadjusted	5.33	0.62	5.6	−0.74	1.18	1.03
Adjusted	4.76	0.59	4.2	−0.84	0.90	0.74
Ontario (ON)				*Southeastern Canada (SE)*		
Unadjusted	−0.35	1.03	0.39	0.35	0.24	1.43
Adjusted	−0.60	0.57	−0.38	0.56	−0.19	0.74

*Significant at the 5% level ($\alpha = 0.05$).

non-parametric Kendall's tau-based estimator (Sen 1968) to estimate trends in the regionally averaged unadjusted and adjusted precipitation totals over the 1971–2000 period (the three decades with the highest number of stations; see Fig. 2). An iterative procedure, originally proposed by Zhang, Vincent, Hogg, and Niitsoo (2000) and refined by Wang and Swail (2001), was adopted to take the effect of lag-1 autocorrelation into account when testing the significance level of a trend. As shown in Table 2, for both northern and southern Canada, the trend is slightly larger in the adjusted than in the unadjusted data for the cold season total precipitation, especially in southern Canada, but it is smaller for the warm season and annual totals. Also, the 1971–2000 trends are significant at the 5% level for the cold season and annual total precipitation averaged over northern Canada and not significant for all other cases in Table 2. In other words, the adjustments did not change the significance of the trends at the 5% level but affected the magnitudes of the trends for southern and northern Canada.

As shown in Table 2, the trend is slightly smaller in the adjusted than in the unadjusted data for British Columbia for both cold and warm seasons, and for the Prairies and Ontario in the warm season. For southeastern Canada, the sign of the trend changed from positive in the unadjusted data to negative in the adjusted data (Table 2). In terms of trend in the annual total precipitation, the trend is slightly smaller in the adjusted than in the unadjusted data for British Columbia, the Prairies, and southeastern Canada, while the sign of the trend in Ontario changed from positive in the unadjusted data to negative in the adjusted data (Table 2). However, none of these sub-regional trends in Table 2 are statistically significant at the 5% level for both the unadjusted and adjusted data.

Note that the regional averages here were limited to the 30-year period of 1971–2000. Thus, the adjustments could still affect the significance of trends in regional average precipitation totals over a longer time period as well as in individual station series. Also, caution should be exercised when interpreting the results for northern Canada because the number of stations there is very limited, although the spatial coverage was relatively stable from 1971 to 2000.

5 Correction for miscoded missing values

We noticed that, in the ECCC digital archive, days with missing observations over a prolonged period at some stations were mistakenly filled with a precipitation amount of zero instead of a missing value code (-999.9). Such mistakes (miscoded missing values) result in long runs (up to seven years) of zero monthly total precipitation. In other words, such mistakes can easily be identified by flagging all long runs of zero monthly total precipitation for further investigation. This approach is more effective than checking the daily data series directly because there are substantially more valid zero values in a daily precipitation data series than in the corresponding monthly total precipitation data series, especially in Canada. We took this approach in our study to identify long runs of miscoded missing values, as described below.

Considering that it is rare for a Canadian station to have a dry spell that lasts for three or more months, we flagged all periods of zero monthly precipitation for three or more consecutive months as suspect periods of miscoded missing values. We checked the daily data for each of these suspect periods against daily data from nearby stations to identify the exact periods for which zero should be replaced with the missing value code. Note that the screening procedure above could allow shorter periods (<3 months) of miscoded missing values to go undetected. The focus here is limited to correcting long runs (≥3 months) of miscoded missing values.

In the calculation of monthly precipitation totals from daily values for each of the 3346 stations, we used zero tolerance for missing values. In other words, a monthly value is considered missing if that month has one or more missing daily observations. The Adjusted and Homogenized Canadian Climate Data (AHCCD) monthly precipitation totals were derived in a different manner with the following rules used for missing values: a value for a month was considered missing if that month had more than five days of missing values in total or had a period of four or more consecutive days of missing values (Mekis & Vincent, 2011). Such a high tolerance for missing values results in underestimated monthly precipitation totals, especially at seasonal stations where observations are missing for all wet days during the season (usually the cold season) when the gauge is not in operation while observations are complete for all the dry days. Such underestimates can be avoided by using zero tolerance, which will result in a larger number of missing monthly values. However, it is better to allow a gridding algorithm to estimate the missing monthly values from the more accurate values at nearby stations than using false zero monthly values to generate a gridded dataset.

We identified and corrected 74 periods of miscoded missing values at 54 stations in the AdjDlyRS version 2016 dataset. Some of these are seasonal stations, with the zeroes being filled throughout the out-of-operation season (e.g., winter). When using the aforementioned AHCCD tolerance for missing values to calculate monthly total precipitation, we found an additional 41 long runs (≥3 consecutive months) of zero monthly precipitation for 13 more stations in the AdjDlyRS version 2016 dataset. These are mainly seasonal stations with missing observations for all wet days throughout the out-of-operation season.

6 Concluding remarks

We have developed an adjusted daily rainfall and snowfall (AdjDlyRS) dataset for Canada using the special metadata database that we started to develop about 10 years ago. The latest version (version 2016) of the AdjDlyRS dataset includes 3346 stations with up to 177 years of data during the period from 1840 or later to February 2016 (Fig. 2). These are all manual stations for which we have the metadata needed for various adjustments (there are many other manual stations that we do not have the metadata needed to carry out the adjustments; see the last paragraph of this article).

The procedures and methods for adjustment and corrections were adapted from previous studies with some generalization as described in Section 3.b to determine the rain-gauge types due to missing metadata.

Applying the SWE adjustments increased the precipitation amount over most areas of Canada except the Rocky Mountains where it decreased the precipitation amount. Trace and rain-gauge-related corrections always increase precipitation totals although they only partly compensate for the underestimate in total precipitation caused by the use of the assumed 10:1 SWE ratio. Changes to the long-term mean total precipitation in the adjusted dataset were comparable with those in Mekis and Vincent (2011) who carried out the adjustments for a much smaller number of stations.

In summary, our results show that the original unadjusted total precipitation data underestimate more than 25% of the total precipitation in northeastern Canada and about 10–15% in most of southern Canada. Such large underestimates make the unadjusted data unsuitable for water availability and/or balance studies, numerical model validation, and many other applications. The trace correction adds 5–20% to the precipitation in northern Canada but less than 5% in southern Canada. The gauge-related corrections do not show an organized spatial pattern but add 5–10% to the precipitation at 312 stations.

In addition, we have corrected the data for missing values that were miscoded as zero (see Section 5). We believe that the adjustments have diminished some inhomogeneities associated with changes in rain-gauge type and observation procedures although other inhomogeneities related to other artificial changes such as changes in rain-gauge rim height and relocation of a rain gauge may still exist in the adjusted dataset. Procedures such as those proposed in Wang, Chen, Wu, Feng, and Pu (2010) may still be needed to homogenize the AdjDlyRS dataset, which we plan to investigate.

The latest version of the AdjDlyRS dataset is available from the Canadian Open Data Portal (http://open.canada.ca/data/en/dataset/d8616c52-a812-44ad-8754-7bcc0d8de305). We will update this dataset as long as rainfall and snowfall data are still collected manually from some stations in Canada. This dataset is suitable for producing gridded precipitation datasets (including precipitation reanalysis). However, long-term records in this dataset are also suitable for climate change studies, and more long-term records can be formed for climate change studies by joining some of these stations with a data homogenization procedure, which we plan to do in the near future.

The Climate Research Division is also working towards adjusting precipitation data from automatic gauges (such as Geonor and Pluvio gauges). These data, along with data from 98 long-term Nipher gauge stations and from 114 Belfort or Fisher & Porter weighing gauge stations, as well as the AdjDlyRS dataset, will be included in the next version of Canada's Daily Integrated Precipitation dataset, which will be used along with the Global Historical Climatology Network (GHCN) daily precipitation dataset for stations in the United States and Mexico to produce a precipitation reanalysis dataset for North America using the CaPA approach (Lespinas et al., 2015). The dataset is being used along with the Australian National University spline interpolation (ANSUPLIN; Hutchinson et al., 2009), which is a thin-plate smoothing model, to produce version 1 of the ANUSPLIN-gridded daily and monthly precipitation datasets for North America.

Note that the SWE adjustments applied in this study are climatological adjustments because the same SWE adjustment factor was applied to all snowfall ruler measurements at one site. However, the SWE ratio actually depends on the weather regime (i.e., snowfall on some days could be wetter or drier than on other days). Regime-dependent adjustments can be developed and may be one of our future projects. We have also performed the SWE correction for more than 3800 other stations, but we do not have the metadata needed to carry out other adjustments (trace, gauge undercatch, and wetting loss) for these stations. We will perform the adjustments if the needed metadata can be found.

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Disclosure statement

No potential conflict of interest was reported by the author.

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