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# Observed Changes in Canada's Snowfall as Inferred from Precipitation and Daily Mean Temperatures

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**ABSTRACT** Limited long-term snowfall observations make it difficult to document how snowfall is changing across Canada. Proxy snowfall measures derived from more plentiful temperature and precipitation may therefore be helpful. We consider simple partitioning of daily precipitation into rainfall and snowfall based on whether temperature is above or below either 0°C or a station specific threshold. Using daily mean temperature and the fixed 0°C threshold resulted in more accurate estimates of annual and seasonal snow-day number and water equivalent snowfall amount than using daily maximum or daily minimum temperature. Using station-specific thresholds further improved estimation accuracy. Trends estimated from these proxy snowfall indices well match those estimated from observed snowfall data for periods and locations when both are available. The median annual proxy snowfall amount in Canada derived from homogenized daily precipitation and temperature data decreased 2.5% per decade over 1949–2023 south of 60°N and increased 0.5% per decade north of 60°N. Seasonally, annual proxy snowfall amount has changed most rapidly in winter, declining 2.6% per decade in southern Canada and increasing 3.6% per decade in northern Canada. This simple approach improves prospects for the continuation of long-term snowfall monitoring in Canada by exploiting long-term daily precipitation and temperature data.

**RÉSUMÉ** [Traduit par la rédaction] Le nombre limité d'observations à long terme sur les chutes de neige rend difficile la documentation des changements qui s'opèrent à cet égard à travers le Canada. Des mesures indirectes des chutes de neige dérivées de données plus abondantes sur la température et les précipitations peuvent donc s'avérer utiles. Nous envisageons une simple répartition des précipitations quotidiennes en pluie et en neige, selon que la température est supérieure ou inférieure à 0 °C ou à un seuil propre à chaque station. L'utilisation de la température moyenne quotidienne et du seuil fixe de 0 °C a permis d'obtenir des estimations plus précises du nombre annuel et saisonnier de jours de neige et de la quantité de neige équivalente en eau que l'utilisation de la température maximale ou minimale quotidienne. L'utilisation de seuils propres à chaque station a encore amélioré la précision des estimations. Les tendances estimées à partir de ces indices de neige proxy correspondent bien à celles estimées à partir des données d'observation des chutes de neige pour les périodes et les lieux où les deux sont disponibles. La quantité annuelle médiane de neige estimée au Canada, calculée à partir de données homogénéisées sur les précipitations et les températures quotidiennes, a diminué de 2,5 % par décennie entre 1949 et 2023 au sud de 60° N et a augmenté de 0,5 % par décennie au nord de 60° N. Sur le plan saisonnier, la quantité annuelle estimée de neige a changé le plus rapidement en hiver, diminuant de 2,6 % par décennie dans le sud du Canada et augmentant de 3,6 % par décennie dans le nord du Canada. Cette approche simple améliore les perspectives de poursuite de la surveillance à long terme des chutes de neige au Canada en exploitant les données quotidiennes à long terme sur les précipitations et les températures.

**KEYWORDS** climate change; precipitation partitioning; empirical methods; snowfall indices; long-term trends

## 1 Introduction

Snowfall is a very important type of precipitation because snow regulates Earth's climate by reflecting solar radiation,

acts as a vital freshwater reservoir, insulates the ground to protect plants and wildlife, and supports ecosystems and human activities such as transportation, hydropower,

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agriculture, and winter recreation. Snow that accumulates on the land surface during the cold season serves as a natural seasonal water reservoir and also provides thermal insulation for overwintering crops to enable their survival during harsh winters (Bélangier et al., 2002; Qian et al., 2024). Snowmelt in the warm season releases water from the snowpack into the soil and produces runoff to recharge rivers and groundwater. Snow cover is also an important component of the climate system as it strongly affects the land-surface albedo and insulates the atmosphere from the underlying high heat-capacity land surface. Therefore, changes in snowfall, and further in snow cover, may result in a series of consequences to the climate system, ecosystems and socioeconomic activities (Chai et al., 2025). For example, observed changes in the seasonality of streamflow in many of Canada's drainage basins include a shift to an earlier spring freshet, higher winter flows, and reduced summer flows (Bonsal et al., 2019; Najafi et al., 2017) that result from snowpack changes and could have inevitable socioeconomic consequences because of water availability.

Historical northern hemisphere snow cover decreased over the 1981–2018 period in all months, with the decline in snow cover exceeding  $50,000 \text{ km}^2 \text{ yr}^{-1}$  during November, December, March, and May (IPCC, 2021; Mudryk et al., 2020). A decreasing trend in snow cover fraction has also been observed in Canada, with coverage declining between 5% and 10% per decade since 1981 (Derksen et al., 2019). The reductions in snow cover extent are strongly related to increasing surface temperatures (Mudryk et al., 2017) and have been linked to anthropogenic influence (Estilow et al., 2015; Najafi et al., 2017). Only a few studies, however, have directly linked trends in snow cover to observed changes in snowfall.

Most studies of observed snowfall changes in Canada have focused on a limited number of individual locations. An exception is Vincent et al. (2018) who reported trends in the number of days with snowfall at 464 stations across Canada. A decline of 1.6 days over the 1948–2012 period in the annual number of days with snowfall was detected for Canada and all regions except northern Canada (situated above  $60^\circ\text{N}$ ), where a statistically significant increase of 7.3 days in the annual number of days with snowfall was found for the 1948–2012 period. Analysing the 50 years (from 1970/71 to 2019/20) of temperature and precipitation data observed at the five most populated cities in Ontario, Hewer and Gough (2023) found that total snow days, total wet days (days with total precipitation greater than 0.2 mm), and the snow-day fraction (total snow days divided by total wet days) in winter (1 December–31 March) decreased significantly in four of five locations. Ahmed et al. (2022), considering the extended November and April cold season for a similar period, reported decreasing trends in snowfall and increasing trends in rainfall, with no significant trends in total precipitation across Ontario. Newton et al. (2021) found decreases in cold season precipitation and a shift from snow to rain to dominate the period of 1950–2017 in Alberta. Most of these studies, however, provide only

regional results rather than national coverage and may also be subject to large uncertainties due to inhomogeneities in the station data.

The rapid decline in the number of stations reporting daily snowfall has caused large uncertainties for studies based on in-situ snowfall observations. Notably, the period considered by Vincent et al. (2018) is limited to 1948–2012 for this reason. Among 425 critical long-term stations in Canada (Wang et al., 2023), snowfall observation had ended at 208 (one half of the total) by 2011 and at 320 stations (three quarters of the total) by 2016. Only 61 of 425 stations reported snowfall in 2023. This rapid loss of daily snowfall data is primarily caused by a replacement of manual stations with automated counterparts that do not separate precipitation into rainfall and snowfall. A key motivation of this study, therefore, is to determine whether a simple proxy for observed snowfall data based on homogenized precipitation and temperature data would be useful in monitoring ongoing snowfall change. A homogenized daily precipitation dataset for the 425 critical long-term stations, CanHomP dly V2 (Wang & Feng, 2025), has been developed and will be updated regularly in the future. This dataset may be useful for assessing changes in snowfall, such as changes in annual and seasonal snowfall amount and frequency, if an appropriate approach can be used to estimate daily snowfall amount, i.e. proxy snowfall data, from daily precipitation data and other commonly available climate data such as surface air temperature data.

There are many pathways for precipitation in various forms to reach the surface depending on temperature and moisture conditions above or at the surface (Bourgoin, 2000; Stewart et al., 2015). Several methods have been developed to partition daily precipitation into liquid and frozen components. Most methods use air temperature thresholds to partition daily precipitation into rainfall and snowfall (Bergström, 1995; Pipes & Quick, 1977; Rango, 1995) while a few also involve other surface variables such as wet-bulb temperature and humidity (Ding et al., 2014; Harder & Pomeroy, 2014; Jennings et al., 2018; Marks et al., 2013), as well as upper air variables, such as the 700–850-hPa thickness (Heppner, 1992), in some cases. Some methods require a vertical temperature profile (Bourgoin, 2000) and sub-daily atmospheric data (Dai, 2008). While the performance of these methods varies widely (Chen et al., 2014; Luo et al., 2020; Su et al., 2022), the application of these methods is often constrained by the availability of data for the required climate variables. Methods based on temperature thresholds tend to be applied most often as air temperature data are more commonly collected with daily precipitation data than other variables.

The most common temperature-based methods include a model with a single fixed temperature threshold  $T_a$  to separate snowfall and rainfall and a dual-threshold method with two temperature thresholds  $T_s$  and  $T_r$ . The single-threshold method assumes that all precipitation occurring at a temperature below  $T_a$  is snowfall and that all other precipitation is rainfall. When two thresholds are used, a gradual change of

the proportion of rainfall and snowfall, often a linear transition, is applied to precipitation occurring at temperatures between  $T_s$  and  $T_r$ , in addition to regarding all precipitation occurring at a temperature below  $T_s$  as snowfall and above  $T_r$  as rainfall. Kienzle (2008) used an S-shaped curve instead of a linear transition for 15 climate stations across southwestern Alberta, ranging across an area that includes prairie and alpine regions. In addition to various values of the temperature thresholds, either daily mean or maximum and minimum temperatures are used in different studies.

Previously studied precipitation partition methods have mostly focused on their accuracy in determining daily precipitation type. Although these methods perform reasonably well in reproducing observed snowfall frequency and proportion of snowfall to precipitation in most studies (Chen et al., 2014; Hu et al., 2024; Kienzle, 2008; Luo et al., 2020), they are seldom assessed for their use in investigating trends in annual and seasonal snowfall amount and frequency. Due to the lack of long-term observed snowfall data, especially in the context of widespread cessation of direct snowfall amount monitoring, assessing the suitability of precipitation partition methods for investigating changes in snowfall amount and frequency is necessary to ensure that ongoing monitoring of this important aspect of the climate based on station data remains possible.

It is not the intention of this study to find a best partition method to most accurately reproduce observed daily snowfall and rainfall across Canada. Instead, we aim to determine if a simple single-threshold method that uses daily temperature to “partition” daily precipitation into daily snowfall and daily rainfall can produce a proxy daily snowfall dataset that well represents historical changes in annual and seasonal snowfall amount and frequency across Canada. To this end, we compared and evaluated three methods using a simple threshold of either 0°C for all locations or station-specific thresholds that vary between locations, in terms of reproducing annual and seasonal snowfall indices and the observed snowfall trends (see Section 2). Once a proxy daily snowfall dataset suitable for assessing historical changes in snowfall was produced, we analysed it to characterize historical changes in snowfall across Canada (see Section 3).

## 2 Data and methods

The strategy that is used in this study to develop long records of proxy snowfall amounts suitable for trend analysis consists of two primary components that use different data sources. Quality controlled and adjusted station data, including snowfall data, are first used to test, and calibrate as appropriate, several methods for partitioning precipitation into rain and snow. This evaluation results in the selection of a partitioning method that is applied to carefully homogenized daily precipitation and temperature data to produce complete records of daily proxy snowfall amounts covering the period 1948–2023. This section describes the datasets and methods used in implementing this strategy.

### a Data

The testing and calibration of the partitioning methods that we consider requires daily snowfall and precipitation observations and closely co-located daily surface air temperature data (measured at a height of 2 m).

The daily snowfall and precipitation data used for testing and calibration are obtained from the AdjDlyRS dataset (Wang et al., 2017), which includes adjusted daily rainfall and snowfall data from 3346 manual observing stations across Canada, most of which have short data records. The snowfall data are ruler measurements that were converted to their water equivalent (SWE) amounts using the SWE ratio map for Canada developed by Mekis and Brown (2010). The rainfall data have been adjusted for gauge-related issues, including under-catch and evaporation caused by wind effects, gauge-specific wetting losses, and various data flags (Wang et al., 2017). This dataset is now routinely updated and quality controlled using the quality-control procedure of Cheng et al. (2024), which includes the identification of missing values that had not been coded as missing in the climate archive. The version updated to the end of September 2019 was used in this study. This dataset includes adjusted rainfall and snowfall, separately, as well as the sum of rainfall and snowfall as the daily (total) precipitation. Daily maximum and minimum surface air temperature data from sites that are co-located with the snowfall and precipitation observations are extracted from the Environment and Climate Change Canada’s digital archive and have been quality controlled and post-processed following the method of Hutchinson et al. (2009). Daily mean surface air temperature, which is also used, is obtained by averaging daily maximum and minimum temperatures on the same day.

Results from testing and calibration will be applied to long-term homogenized daily precipitation records from the CanHomP dataset (Wang et al., 2023), and thus the observational snowfall data that we extracted from the AdjDlyRS was for stations that correspond to those in CanHomP. Since current automated gauge stations report only total precipitation, snowfall data are not available from all the 425 stations, nor for the entire data record periods. Only 80 out of the 425 stations have snowfall data up to 2019. The period of snowfall data also varies from station to station. Five out of the 425 stations have no snowfall data at all, 26 stations have 2–29 years of snowfall data, while 388 stations (Fig. 1) have at least 20 complete years of daily snowfall data together with daily total precipitation and daily temperature data, which however start and end in different years. We used the snowfall data at these 388 stations to evaluate the snowfall partitioning methods. Although the period of snowfall data varies from station to station, the observed snowfall data and the derived proxy snowfall data for evaluation of partitioning methods for the same station always cover the same period.

It is important to note that while these data are quality controlled, they are not homogenized, which may affect the calculation of proxy snowfall amounts.

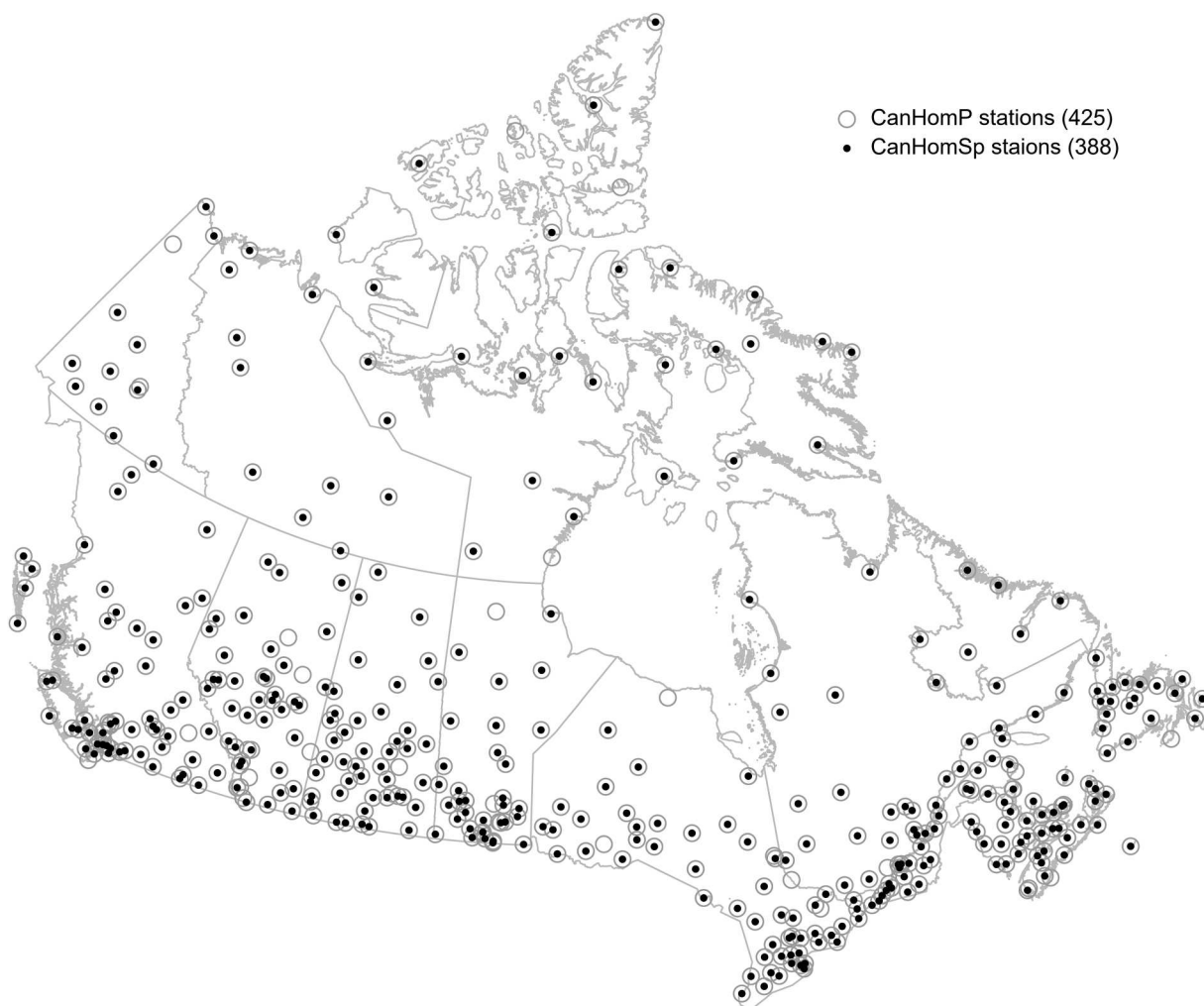


Fig. 1 Spatial distribution of the 388 stations with at least 20 years of complete observed snowfall data over the 425 long-term critical precipitation stations in the CanHomP dataset.

Many of the 425 long-term records were created by joining shorter records from nearby stations and thus incorporate data from substantially more than 425 different physical locations (Wang et al., 2023). When the station joining is needed, daily snowfall and temperature data were joined the same way as the total precipitation data for the purpose of this study. Thus, all the daily temperature, snowfall, and precipitation data used in the evaluation were always observed at the same station. Maintaining the synchronicity of observations in this way ensures that the effects of inhomogeneity due to station joining on the estimation of station-specific snow-rain temperature thresholds are minimized.

As a second step, long-term proxy snowfall data for 1949–2023 are produced using carefully homogenized daily precipitation and temperature data.

The homogenized daily precipitation data are taken from version 2 of the Canadian Homogenized Precipitation daily dataset, CanHomP dly V2 (Wang & Feng, 2025). A unique feature of CanHomP dly V2, which provides coverage to the end of June 2024, is that all temporal data gaps have been infilled for the period considered in this study. In

general, Canada's long homogenized daily temperature records, such as those that comprise CanHomT V3.1 (updated from Vincent et al., 2020), are not collocated with CanHomP dly V2 records. We therefore use daily temperature data corresponding to those locations that are derived from the gridded version of CanHomT V3.1 dataset, CanGridT dlyV3.1 (Wang et al., 2025) for deriving long-term (1949–2023) proxy snowfall data.

#### **b** *Precipitation partitioning methods*

A simple threshold of 0°C is often employed when temperature is used to partition precipitation into snowfall or rainfall (e.g. Luo et al., 2020; Marks et al., 2013). We considered three variants of this approach, comparing either daily maximum, daily minimum or daily mean surface air temperature ( $T_{\max}$ ,  $T_{\min}$  or  $T_{\text{mean}}$ ) with 0°C, which we refer to as the Tx0, Tn0, and Tm0 methods, respectively. Daily precipitation is considered as snowfall if the daily temperature in question is below 0°C, and as rainfall otherwise.

While attractive for its simplicity, the surface air temperature at which precipitation typically changes from rain to

snow is often observed to be different from 0°C, reflecting local meteorological conditions under which such transitions occur. A slightly more complex empirical approach to classifying daily precipitation amounts as rainfall or snowfall is therefore to replace the fixed 0°C threshold with local thresholds.

We estimate such thresholds for the 388 stations with sufficient snowfall amount data that are identified above. These stations provide reasonably good coverage of the 425 CanHomP stations (Fig. 1), thus the availability of daily snowfall, total precipitation and temperature observations at these locations offer a good opportunity to investigate the potential for using station-specific thresholds in this study. The three variations of this method using daily maximum, daily minimum or daily mean surface air temperature with station-specific thresholds are referred to as the Txc, Tnc, and Tmc methods respectively hereafter. Station-specific thresholds were determined by an iterative procedure to minimize the root mean squared error of annual snowfall amount derived from the estimated and observed daily snowfall.

### c Snowfall indices

The annual and seasonal snowfall indices analysed in this study include annual and seasonal total snowfall amount (SA), number of snow-days (SD, days), snow- to precipitation-amount ratio (S2PAR), and snow- to precipitation-day ratio (S2PDR). We express snowfall amounts in units of mm of water equivalent (SWE). Annual indices are calculated for each “snow year”, which extends from 1 August to 31 July of the following year, with values labelled by the year in which the snow year ends. A snow-day is a day with snowfall amount greater than 1.0 mm SWE; and a precipitation-day is a day with total precipitation greater than 1.0 mm. Seasonal snowfall indices are calculated for autumn (SON: September-October-November), winter (DJF: December-January-February), and spring (MAM: March-April-May). Summer (JJA: June-July-August) is not included as snowfall rarely occurs in summer, especially in southern Canada.

### d Evaluation criteria

Partitioning methods are evaluated by comparing indices derived from observed and proxy snowfall amounts at locations where snowfall observations are available. The evaluation is performed in terms of bias (mean error ME) and root mean squared error (RMSE), which combines bias with the variance of the proxy versus observed differences. Given the large spatial differences in annual and seasonal mean values of the indices, ME and RMSE of the snowfall indices are expressed relative to their mean values (denoted RME and RRMSE). ME, RME, RMSE, and RRMSE are calculated separately for each station.

Several metrics are also used to evaluate how the trends in the snowfall indices estimated from observed snowfall data are reproduced by proxy snowfall data. These include (i) the pattern correlation (Pearson correlation between the

trend magnitudes estimated from observed and proxy snowfall data across all stations), (ii) root mean squared trend difference (RMStrD, similar to RMSE except for trend), (iii) matching rate of statistically significant positive trends (the number of stations with a statistically significant positive trend estimated from both observed and proxy data divided by the number of stations with a statistically significant positive trend estimated from observed data), (iv) matching rate of statistically significant negative trends (similar to the matching rate of statistically significant positive trends except for statistically significant negative trends), and (v) matching rate of negative/positive trends (similar to the matching rate of statistically significant positive trends except for negative/positive trends either statistically significant or not).

### e Trend analysis method

We used a nonparametric Kendall’s tau-based slope estimator (Sen, 1968) to compute trends with an iterative procedure, originally proposed by Zhang et al. (2000) and refined by Wang and Swail (2001) to take the effect of lag-1 autocorrelation into account when testing the significance level of a trend. This trend analysis procedure can handle missing data in the data series and in contrast to standard linear regression, is robust to the effect of potential outliers in short data segments at the beginning or end of the series that may be separated in time from other parts of the series. The trend analysis was performed for each station, and a  $p$ -value was obtained in each test. A trend is considered statistically significant if the  $p$ -value is smaller than the specified significance level  $\alpha$  (i.e. 0.05 in this study). A log-odds transformation is applied to indices that count the annual and seasonal numbers of snow-days (SD) before applying conventional regression models to estimate significance of trends to ensure that they have characteristics necessary for reliable trend analysis (see Wang (2006) and Hanesiak and Wang (2005)). For easy comparison with other indices, trend magnitudes for SD were also estimated directly from the count data (without the log-odds transformation).

## 3 Results and discussion

### a Accuracy in reproducing the observed snowfall indices when partitioning at 0°C

We first consider performance of the three methods that use 0°C to distinguish between rain and snow.

The Tm0 method performed better than the Tx0 and Tn0 methods (Fig. 2), showing consistently smaller biases for annual snowfall amount (SA) and number of snow-days (SD), in terms of either mean error (ME) or relative ME (RME). Averaged across the 388 stations, RME is  $-5.0\%$  for annual SA, and  $-10.6\%$  for annual SD, respectively (Table 1). These RMEs are equivalent to MEs of  $-4.4$  mm and  $-3.1$  days (Table S1). In contrast, the Tx0 method underestimated annual SA and SD by substantially larger amounts while the Tn0 method substantially overestimated annual SA and SD at most locations (Fig. 2). In addition, the RME range

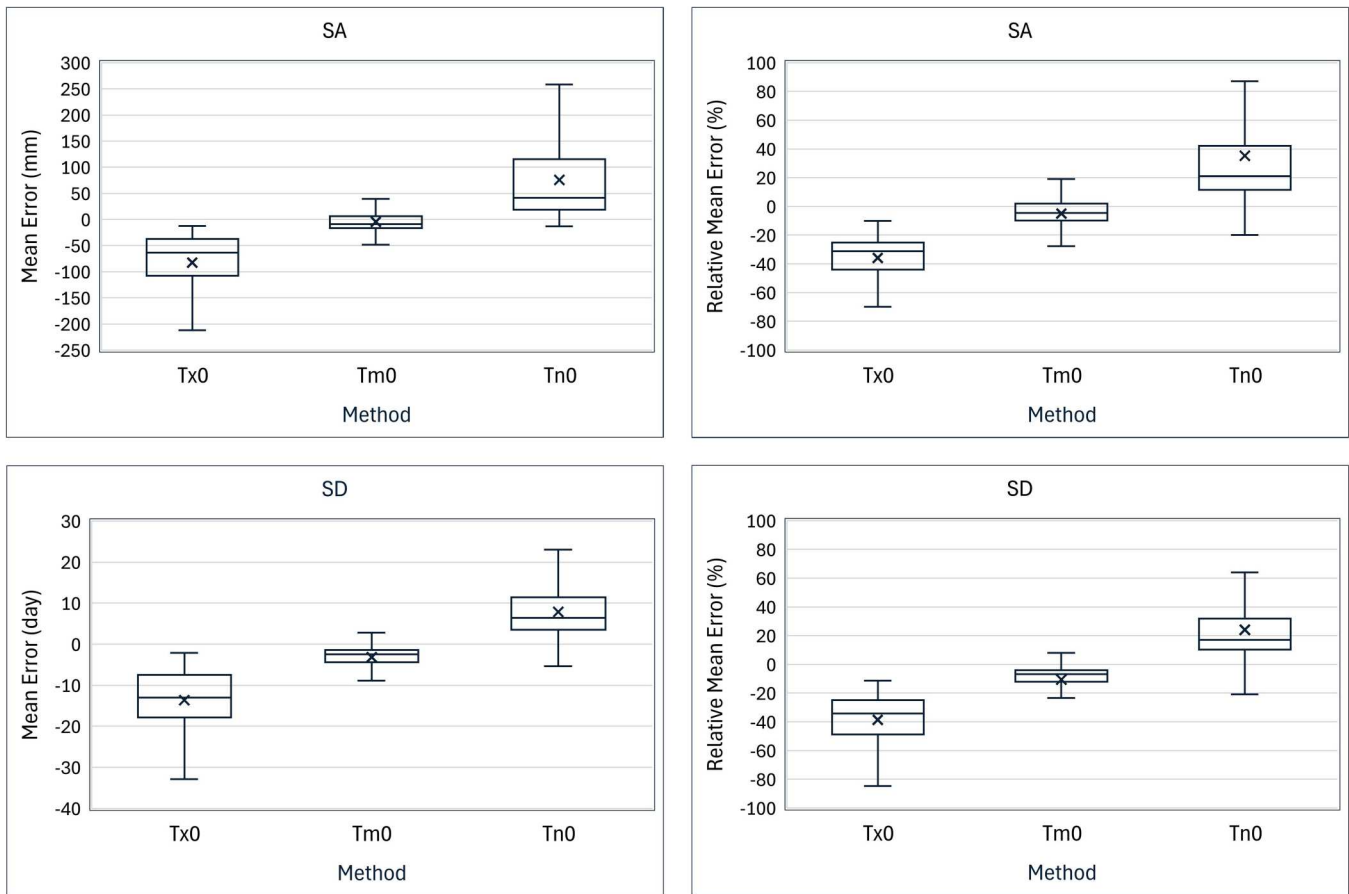


Fig. 2 Boxplots of ME and RME across all stations for annual snowfall amount (SA), number of snow-days (SD), using three methods with a single temperature threshold (Tx0,  $T_{max} < 0^{\circ}C$ ; Tn0,  $T_{min} < 0^{\circ}C$ ; and Tm0,  $T_{mean} < 0^{\circ}C$ ). The boxes show the lower and upper quartiles with the median (horizontal line) and the mean (x). The whiskers show the minimum and the maximum values excluding outliers.

across all stations is much smaller for Tm0 than the other two methods (Fig. 2), implying generally better applicability of the Tm0 method across the country. Tx0 and Tn0 were therefore excluded for further analysis.

The Tm0 relative error metrics RME and RRMSE are greater in fall and spring than in winter (Table 1). Relative errors are often larger for the transition seasons SON and MAM than for DJF and annual snowfall indices (Table 1), presumably because snowfall amounts tend to be smaller in the shoulder seasons and temperatures are more often near  $0^{\circ}C$ . As the errors in S2PAr and S2PDr are mostly inherited from those in SA and SD, respectively, further evaluation results are presented only for SA and SD.

Overall, mean errors are smaller than 5% of observed values for indices calculated from the proxy snowfall data for approximately one-third of stations, and smaller than 10% for two-thirds of stations and larger than 20% for less than 15% of stations (Table 2) when the Tm0 method was used to derive annual snowfall amount (SA). These ranges are comparable with those obtained for annual snowfall amount in a much smaller region (15 stations) in Canada using a single-threshold method similar to the Tm0 method

TABLE 1. Relative mean error (RME, %) and relative root-mean squared error (RRMSE, %), averaged across all 388 stations, for annual and seasonal snowfall indices estimated using two methods based on daily mean temperatures with a simple threshold of  $0^{\circ}C$  (Tm0) for all stations and station-specific thresholds (Tmc). The better values are shown in bold.

Indices*	Statistics	Method	Annual	SON	DJF	MAM
SA	RME	Tm0	-5.0	-13.2	<b>2.5</b>	-18.0
		Tmc	<b>-1.0</b>	<b>-8.8</b>	3.7	<b>-12.8</b>
	RRMSE	Tm0	18.4	49.5	<b>14.9</b>	41.6
		Tmc	<b>13.2</b>	<b>45.2</b>	16.9	<b>36.0</b>
SD	RME	Tm0	-10.6	-20.0	-2.2	-23.6
		Tmc	<b>-7.4</b>	<b>-15.5</b>	<b>-1.1</b>	<b>-19.2</b>
	RRMSE	Tm0	17.4	42.2	11.7	39.3
		Tmc	<b>14.0</b>	<b>39.4</b>	<b>9.7</b>	<b>35.3</b>
S2PAr	RME	Tm0	-5.0	-12.8	<b>2.5</b>	-18.0
		Tmc	<b>-1.0</b>	<b>-8.3</b>	3.7	<b>-12.9</b>
	RRMSE	Tm0	18.4	48.3	14.8	41.5
		Tmc	<b>13.4</b>	<b>44.2</b>	<b>12.4</b>	<b>36.0</b>
S2PDr	RME	Tm0	-10.5	-19.8	-2.0	-23.4
		Tmc	<b>-7.3</b>	<b>-15.2</b>	<b>-1.0</b>	<b>-19.0</b>
	RRMSE	Tm0	17.4	42.6	11.9	39.7
		Tmc	<b>14.0</b>	<b>40.0</b>	<b>9.9</b>	<b>35.7</b>

\* SA: snowfall amount; SD: number of snow-days; S2PAr: snow- to precipitation-amount ratio; S2PDr: snow- to precipitation-day ratio. SON: September-October-November; DJF: December-January-February; MAM: March-April-May.

TABLE 2. Percentage of stations with selected ranges of RME and RRMSE for annual snowfall indices derived from proxy snowfall data using the Tmc method in comparisons with the Tm0 method.

Method Indices	Tmc		Tm0	
	SA	SD	SA	SD
$-5\% < \text{RME} < 5\%$	93.0	52.1	35.1	30.2
$-10\% < \text{RME} < 10\%$	96.9	76.0	64.4	68.8
$-20\% < \text{RME} < 20\%$	99.5	92.5	87.1	85.8
$\text{RRMSE} < 10\%$	49.2	51.3	26.0	33.8
$\text{RRMSE} < 15\%$	78.4	74.2	57.2	68.6
$\text{RRMSE} < 20\%$	89.9	86.6	75.8	82.2

in this study and a more sophisticated dual-threshold method when the thresholds were not calibrated for individual stations (Kienzle, 2008). Root mean squared errors are smaller than 10% of observed values for indices calculated from the proxy snowfall data for more than 20% of stations, and smaller than 15% for one half of stations, and larger than

20% for less than 30% of stations (Table 2). To place these relative errors in context, it should be noted that the SWE-based proxy is less biased than comparison against observed snowfall using an assumed snow density might indicate. The accuracies of the proxy annual SD are all similar to that of SA (Table 2).

An overestimation of more than 5 mm for annual SA is mainly seen in southern Ontario, southern Quebec and Atlantic Canada while an underestimation of more than 5 mm is found elsewhere across Canada (Figure S1). An RMSE of larger than 30 mm for annual SA is mostly found in eastern Canada, the Rocky Mountains and British Columbia (Figure S2). These spatial differences imply that a simple threshold of 0°C might not be the best choice for all stations across Canada when estimating SA.

Timeseries of annual snowfall amount (SA) and number of snow-days (SD) obtained using Tm0 are shown in comparison with observed data in Figure S3 for a few representative stations across the country. The stations were chosen to be

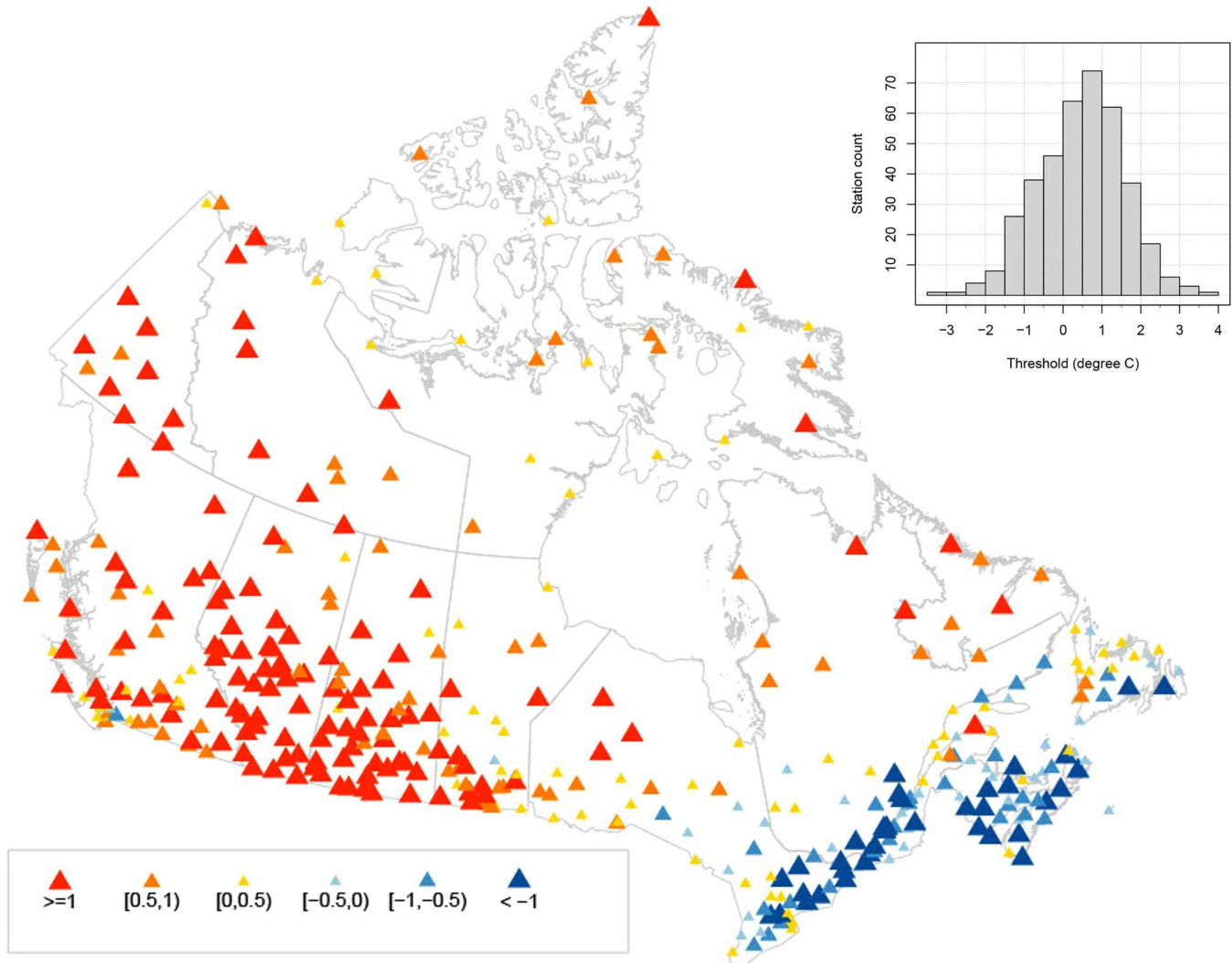


Fig. 3 Spatial distribution and the histogram of station-specific thresholds for daily mean temperature (Tmc) across the 388 stations.

representative of diverse conditions with a relatively long period of snow observation data and relatively low amounts of missing data. Note that neither observed nor proxy data series are homogenized. The timeseries of annual snowfall

indices are generally well reproduced by daily snowfall proxy data, though accuracy varies by location. For example, Tm0 performs much better for Scott, Saskatchewan, on the Canadian Prairies than for Kamloops in the Southern

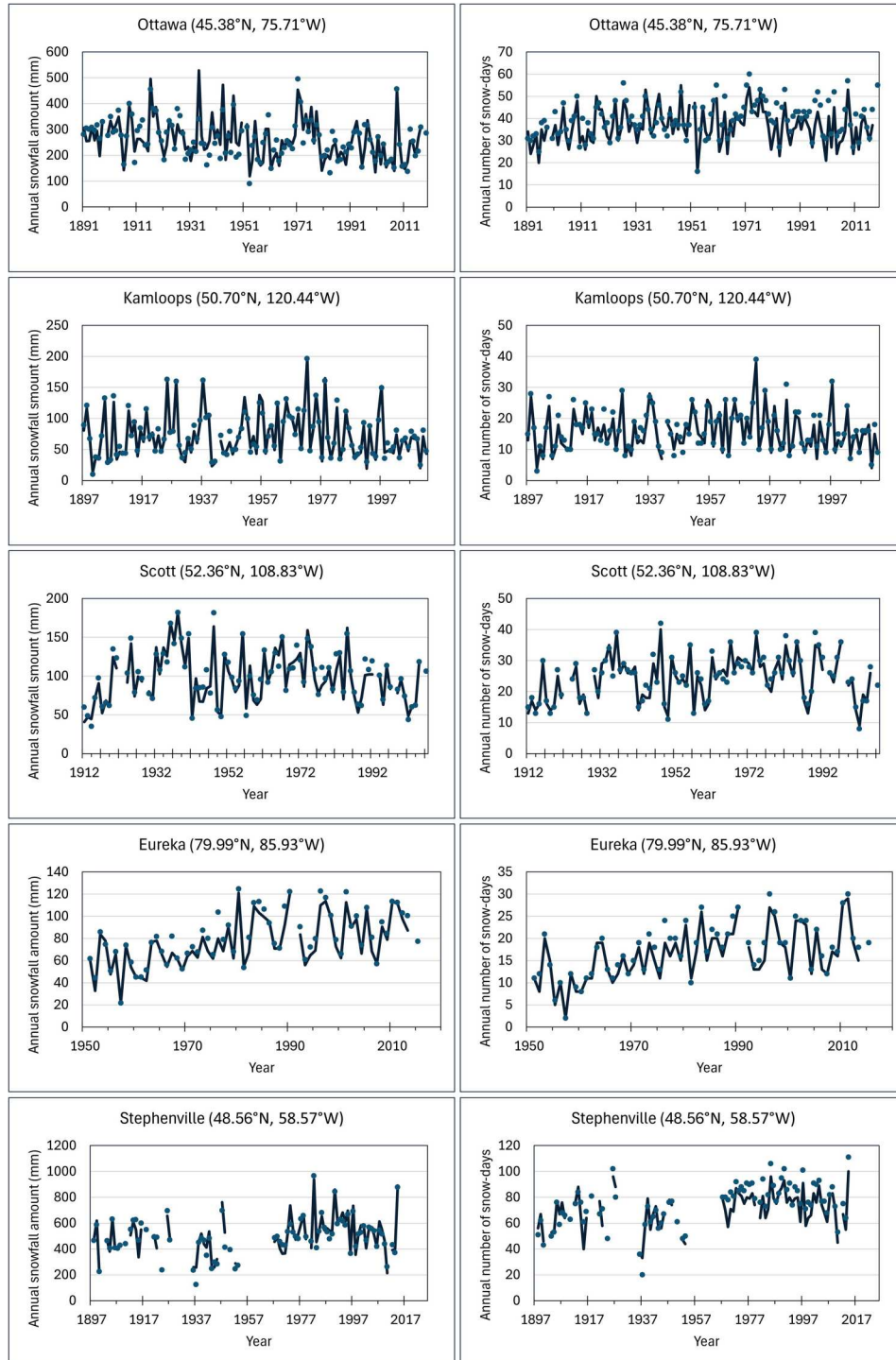


Fig. 4 Observed (blue dots) and estimated (black line) annual snowfall amount (SA) and number of snow-days (SD) using the TmC method for selected locations across Canada. Ottawa (TmC  $-1.3^{\circ}\text{C}$ ; RME and RRMSE respectively for SA: 0.0%, 14.8% and SD:  $-7.7\%$ , 12.7%); Kamloops (TmC  $1.2^{\circ}\text{C}$ ; SA:  $-2.5\%$ , 8.9% and SD:  $-3.8\%$ , 10.7%); Scott, Saskatchewan (TmC  $0.1^{\circ}\text{C}$ ; SA:  $-3.0\%$ , 9.3% and SD:  $-2.3\%$ , 6.6%); Eureka (TmC  $0.8^{\circ}\text{C}$ ; SA:  $-6.2\%$ , 8.9% and SD:  $-6.5\%$ , 9.9%); Stephenville (TmC  $0.8^{\circ}\text{C}$ ; SA: 0.6%, 9.2% and SD:  $-6.1\%$ , 11.0%).

Interior of British Columbia. These examples further indicate that station-specific thresholds should be considered to improve the accuracies of estimated snowfall indices.

### b Station-specific temperature thresholds

The station-specific thresholds varied from  $-3.1^{\circ}\text{C}$  (Grand Manan, New Brunswick) to  $3.9^{\circ}\text{C}$  (Kananaskis, Alberta) across the 388 stations, with a median of  $0.6^{\circ}\text{C}$  and averaged at  $0.5^{\circ}\text{C}$ . A threshold of  $0.0^{\circ}\text{C}$  was determined for 19 stations, i.e. 4.9% of the total stations while a threshold between  $-0.5$  and  $0.5^{\circ}\text{C}$  is seen at 120 (30.1%) stations (Fig. 3). In general, a lower (below  $-1.0^{\circ}\text{C}$ ) threshold is often observed in southern Ontario, southern Quebec and Atlantic Canada while a higher (above  $1.0^{\circ}\text{C}$ ) threshold is seen elsewhere (Fig. 3), matching the spatial pattern of mean error in estimated annual snowfall amount using the Tm0 method (Figure S1). Interestingly, while the correlation between the RRMSE values of annual SA estimated using the Tm0 method and station elevations is only  $-0.04$ , the station-specific thresholds are closely correlated to the station elevations at 0.62. The significant positive correlation of temperature threshold with elevation agrees with Liu and Ren (2024). They found a slightly larger range of temperature thresholds (from  $-1.2$  to  $6.3^{\circ}\text{C}$ ) with a larger positive extension of the temperature thresholds across China that is associated with the high elevations in the Qinghai-Tibet Plateau.

As it was expected, the Tmc method using station-specific thresholds reduces the errors, especially mean errors in annual snowfall amount, on average, compared to the Tm0 method. For example, the average ME is reduced from  $-4.4$  to  $-0.9$  mm (Table S1), corresponding to an improvement from  $-5.0\%$  to  $-1.0\%$  for RME (Table 1). The improvement in the estimation of annual SA is observed across the country (Figure S1 for ME, and Figure S2 for RMSE), although RMSE in the Pacific coast and eastern Canada is still relatively larger than in the Canadian Prairies and northern Canada. In comparisons with annual SA and SD timeseries for five representative stations across Canada, the estimated series using station-specific thresholds are closer to the observed timeseries (Fig. 4) than the timeseries obtained via Tm0 (Figure S3). For example, RME was reduced from  $-18.4\%$  to  $-2.5\%$  for annual SA and from  $-9.6\%$  to  $-3.8\%$  for SD at Kamloops. Collectively, the accuracy of the estimated annual snowfall indices is largely improved by using station-specific thresholds, especially for ME (Figure S4). Mean errors are smaller than 5% of observed values for indices calculated from the proxy snowfall data for 93% of stations, and smaller than 10% for 96.7% of stations and larger than 20% for only 0.5% of stations (Table 2) when the Tmc method was used to derive annual snowfall amount (SA). Accuracy is also improved in terms of RRMSE, as well as for annual number of snow-days. Improvements are also found for seasonal indices, though relative errors are still larger in the shoulder seasons than winter (Table 1 and Table S1).

Tmc, using daily mean temperatures with station-specific thresholds, also performs better than using Txc and Tnc, which use daily maximum temperatures and daily minimum temperatures respectively together with corresponding station-specific thresholds (Figure S5). Txc and Tnc eliminate the large under and over estimation seen of Tx0 and Tn0 methods for annual snowfall amount (Figure S5 vs. Fig. 2), but mean errors (biases) remain larger than for Tmc in terms of overall average and the range across stations. Therefore, Txc and Tnc were excluded from further analysis.

### c Agreement of trends between proxy and observed snowfall data

Trends derived from proxy snowfall data are generally in good agreement with those derived from observed snowfall data for annual and seasonal snowfall indices, for both Tm0 and Tmc (Table 3). Only the results for SA and SD are shown in Table 3 as the results for S2PAr and S2PDr are similar to those for SA and SD, respectively. The pattern correlation for trends of annual and seasonal SA and SD is higher than 0.91 except for DJF SD (0.87 using Tmc and 0.86 using Tm0). In addition, matching rates of negative/positive trends, statistically significant negative/positive trends, are all high except for significant negative trends of SON SD and significant positive trends of MAM SD. Matching rates for trends of DJF snowfall indices are especially high as they are always

TABLE 3. Agreement of trends between observed and proxy snowfall data using the Tmc method in comparisons with the Tm0 method for annual and seasonal snowfall indices (SA: snowfall amounts, and SD: number of snow-days). Better values are in bold.

Indices	Statistics*	Method	Annual	SON	DJF	MAM
SA	Corr	Tm0	<b>0.94</b>	0.93	<b>0.96</b>	<b>0.92</b>
		Tmc	<b>0.94</b>	<b>0.95</b>	0.95	0.91
	RMStrD	Tm0	<b>0.59</b>	0.17	<b>0.31</b>	<b>0.20</b>
		Tmc	0.61	<b>0.14</b>	0.32	<b>0.20</b>
	mNT	Tm0	<b>92</b>	<b>88</b>	<b>93</b>	<b>84</b>
		Tmc	<b>92</b>	83	<b>93</b>	<b>84</b>
	mPT	Tm0	84	<b>73</b>	<b>91</b>	77
		Tmc	<b>88</b>	71	<b>91</b>	<b>80</b>
	mSNT	Tm0	74	50	75	<b>60</b>
		Tmc	<b>81</b>	<b>54</b>	<b>84</b>	50
	mSPT	Tm0	76	63	<b>83</b>	<b>61</b>
		Tmc	<b>79</b>	<b>66</b>	<b>83</b>	<b>61</b>
SD	Corr	Tm0	0.94	0.93	0.86	0.91
		Tmc	<b>0.95</b>	<b>0.94</b>	<b>0.87</b>	<b>0.92</b>
	RMStrD	Tm0	0.09	0.03	<b>0.07</b>	<b>0.03</b>
		Tmc	<b>0.08</b>	<b>0.02</b>	<b>0.07</b>	<b>0.03</b>
	mNT	Tm0	.91	69	90	<b>76</b>
		Tmc	<b>94</b>	<b>72</b>	<b>95</b>	73
	mPT	Tm0	85	73	93	69
		Tmc	<b>88</b>	<b>77</b>	<b>94</b>	<b>71</b>
	mSNT	Tm0	<b>77</b>	<b>75</b>	<b>100</b>	<b>44</b>
		Tmc	69	<b>75</b>	94	<b>44</b>
	mSPT	Tm0	<b>80</b>	<b>51</b>	<b>87</b>	56
		Tmc	77	49	<b>87</b>	<b>60</b>

\*Corr – pattern correlation; RMStrD – root-mean squared trend difference (mm/year for SA and day/year for SD); mNT – matching rate (%) of negative trends; mPT – matching rate (%) of positive trends; mSNT – matching rate (%) of statistically significant negative trends (at the 0.05 level); mSPT – matching rate (%) of statistically significant positive trends (at the 0.05 level).

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higher than 83%. The matching rates are also high for annual snowfall indices. It is worth of noting that Tmc only marginally outperforms Tm0 in terms of agreement of trends between proxy and observed snowfall indices although Tmc largely improves the accuracy of estimated snowfall indices.

Note that snowfall index trends considered here may not necessarily represent snowfall changes across Canada over the 1949–2023 period, given the variations in periods covered between locations and changes in the spatial coverage of the stations that are active at any given time (Wang et al.,

2025). This will be addressed below when we consider trends in proxy snowfall data using long homogenized precipitation and temperature records for the period covering 1949–2023.

Overall, the Tmc method using station-specific thresholds results in reasonably accurate proxy annual and seasonal snowfall indices and performs better than the Tm0 method that uses a simple threshold of 0°C, and other varieties of a single-threshold method using daily maximum/minimum temperatures with either a simple threshold of 0°C or station-specific thresholds. Furthermore, the trends derived

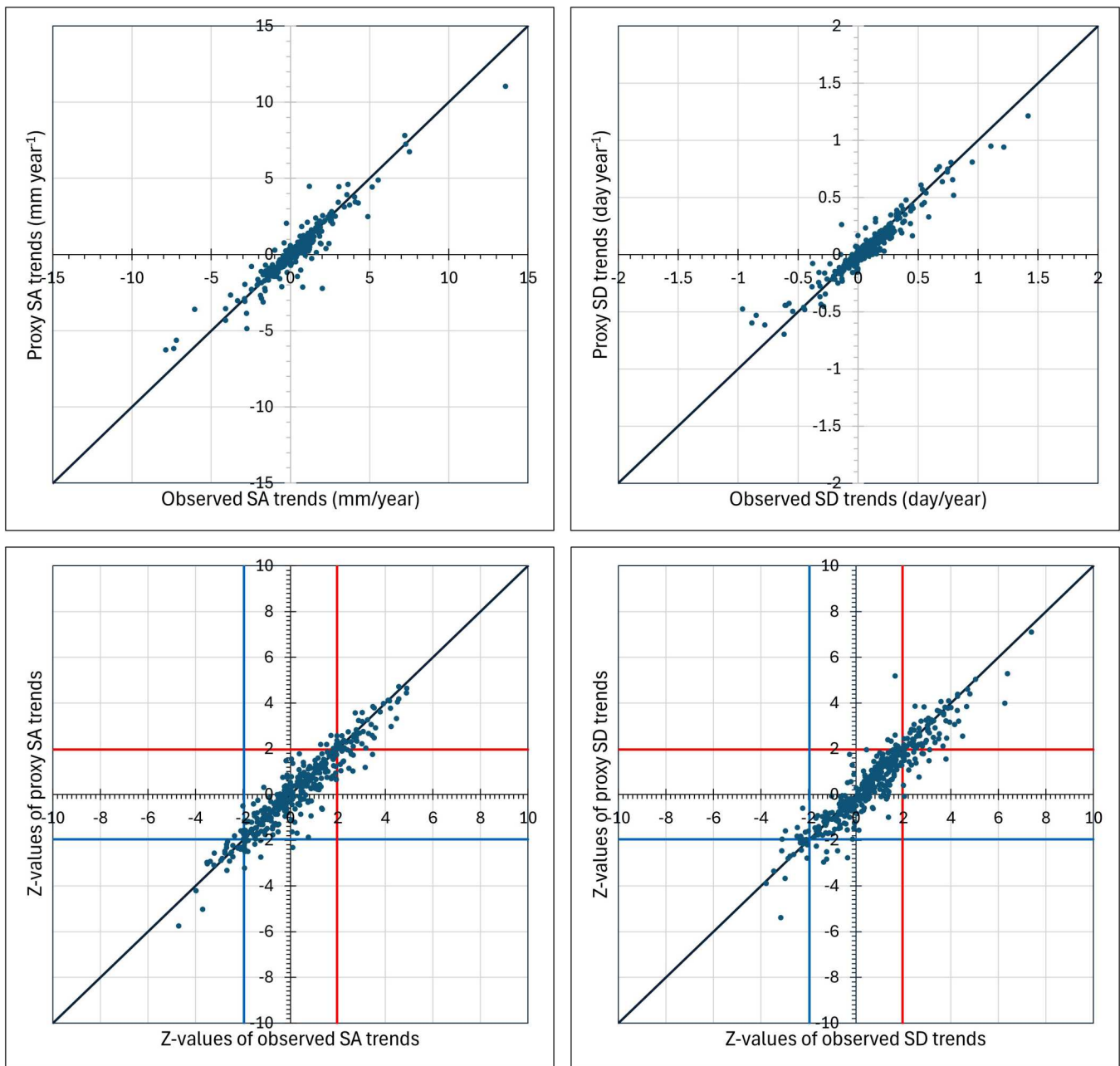


Fig. 5 Comparison of the trends in proxy annual snowfall indices (left panels: SA, snowfall amount; right panels: SD, number of snow-days) and their statistical significance (Z-values) with the corresponding observed counterpart over the period (station dependent) that in situ daily snowfall observations are available at the 425 CanHomP stations (Wang et al., 2023). Z-values below the blue lines (−1.96) or above the red lines (1.96) indicate trends of at least 5% significance. Proxy snowfall data are derived from daily precipitation and temperature using the Tmc method with station-specific temperature thresholds.

from the proxy snowfall indices correspond well to those estimated from observed snowfall data, in terms of their magnitudes, signs and statistical significance (Fig. 5).

#### d Trends for the 1949–2023 period in annual and seasonal proxy snowfall indices

Timeseries of annual and seasonal snowfall indices for the 1949–2023 period were derived by applying the Tmc method to the CanHomP dly V2 dataset and collocated daily mean temperature from CanGridT dlyV3.1. Trends were estimated for each of the snowfall indices at individual stations. Estimated trends are negative at a majority of stations for all annual and seasonal snowfall indices (Table 4). Moreover, trends are statistically significant at more than one third of the stations for annual indices, with a large portion of these stations being negative (Table 4). Similar but often slightly lower percentages of stations are seen for statistically significant trends in seasonal snowfall indices. Notably, no trends were detected for DJF S2PAr and S2PDr at approximately one half of the stations where winter precipitation is still mostly in the form of snowfall. Significant trends in winter that are detected for these proportions are negative.

Most stations with a statistically significant negative trend are found in southern Canada, while those with a statistically significant positive trend are mainly located in northern Canada (Fig. 6). The median of negative trends in annual snowfall amount in southern Canada is  $-6.7$  mm per decade, and  $8.0$  mm per decade for positive trends in northern Canada (Table S2). Annual snowfall amount has decreased in southern Canada but increased at most stations in northern

Canada (Fig. 6(a)), and the annual number of snow-days shows a similar pattern of change while the region along southern Ontario and the St. Lawrence River basin has a mixture of statistically significant increases and decreases (Fig. 6(b)). Both the proportion of the amount of precipitation falling as snow and precipitation days with snow have decreased at most locations across Canada (Fig. 6(c,d)).

Trends across northern stations (north of  $60^{\circ}\text{N}$ , a total of 48 stations) are collectively in contrast to those across southern stations (south of  $60^{\circ}\text{N}$ , a total of 340 stations), not only for annual snowfall amount but also for seasonal amount and the number of snow-days in winter and spring (Fig. 7). The median of trends for annual SA at southern stations is  $-2.5\%$  per decade while it is  $+0.5\%$  per decade at northern stations (Table 5). Similar contrasts are seen for seasonal SA in DJF ( $-2.6$  vs.  $+3.6\%$  per decade), and MAM ( $-2.3$  vs.  $+1.4\%$  per decade). These contrasts are also seen for annual, DJF and MAM SD. The median trend for annual S2PDr is negative at both southern and northern stations,  $-1.7$  vs.  $-0.1\%$  per decade for annual S2PAr and  $-3.4$  vs.  $-1.1\%$  per decade for annual S2PAr (Table 5). Precipitation is still occurring in the form of snowfall in DJF and MAM at northern stations, resulting in a median trend of 0 for snowfall amount and number of snow-day as a proportion to total precipitation and number of precipitation days respectively. The median trends at southern stations in MAM show larger decreases in the proportions of precipitation falling as snow for both precipitation amount and days than the other two seasons, indicating slightly faster changes in snowfall occurring in spring.

Snowfall changes that are generally consistent with those seen in southern Canada have also been reported in the continental United States (CONUS) as can be seen, for example, on the US Environmental Protection Agency Climate Change Indicators web page (<https://www.epa.gov/climate-indicators/climate-change-indicators-snowfall>). It shows that there has been a decrease in the proportion of precipitation falling as snow across most of the CONUS region over a similar 1949–2020 period. In the same time period, a decline in snowfall amount has also been seen at most monitoring stations in the US, except for increases in some parts of the central and western US. The trends derived in this study from proxy snowfall data provide a relatively complete updated view of changes in snowfall across Canada and are mostly consistent with trends detected by other studies in observed snowfall data at a very limited number of locations in Canada (Ahmed et al., 2022; Hewer & Gough, 2023; Newton et al., 2021) and in the United States (Ensor et al., 2009; Feng & Hu, 2007; Zhang et al., 2020).

#### e Limitations of the partition methods

A single temperature-threshold method was employed in this study to partition daily precipitation completely into snowfall or rainfall to develop a proxy daily snowfall series. Our objective was to estimate several annual and seasonal snowfall

TABLE 4. Percentage of stations being detected with a positive trend (PT, either statistically significant or not), a negative trend (NT, either statistically significant or not), a statistically significant positive trend at the significance level of 0.05 (SPT), and a statistically significant negative trend (SNT) in annual and seasonal (SON: September–October–November; DJF: December–January–February; MAM: March–April–May) snowfall amount (SA), number of snow-days (SWE > 1.0 mm) (SD), snow- to precipitation-amount ratio (S2PAr), and snow- to precipitation-day ratio (S2PDr) over the period of 1949–2023 for 388 CanHomSp stations across Canada.

Indices		SA	SD	S2PAr	S2PDr
annual	PT	26.3	31.7	11.3	24.7
	NT	73.7	64.4	88.7	75.3
	SPT	7.7	9.5	0.8	4.4
	SNT	34.0	30.7	46.4	30.7
SON	PT	31.7	22.7	18.6	24.5
	NT	56.2	34.3	68.0	53.6
	SPT	2.1	2.3	0.0	1.3
	SNT	9.0	8.3	19.1	10.8
DJF	PT	31.2	34.0	2.1	2.1
	NT	68.8	58.8	50.3	47.7
	SPT	9.3	12.4	0.0	0.0
	SNT	29.4	25.0	23.5	21.7
MAM	PT	29.4	21.9	7.2	11.3
	NT	62.6	50.5	79.9	70.9
	SPT	5.9	6.7	0.3	0.5
	SNT	15.0	18.8	27.6	18.6

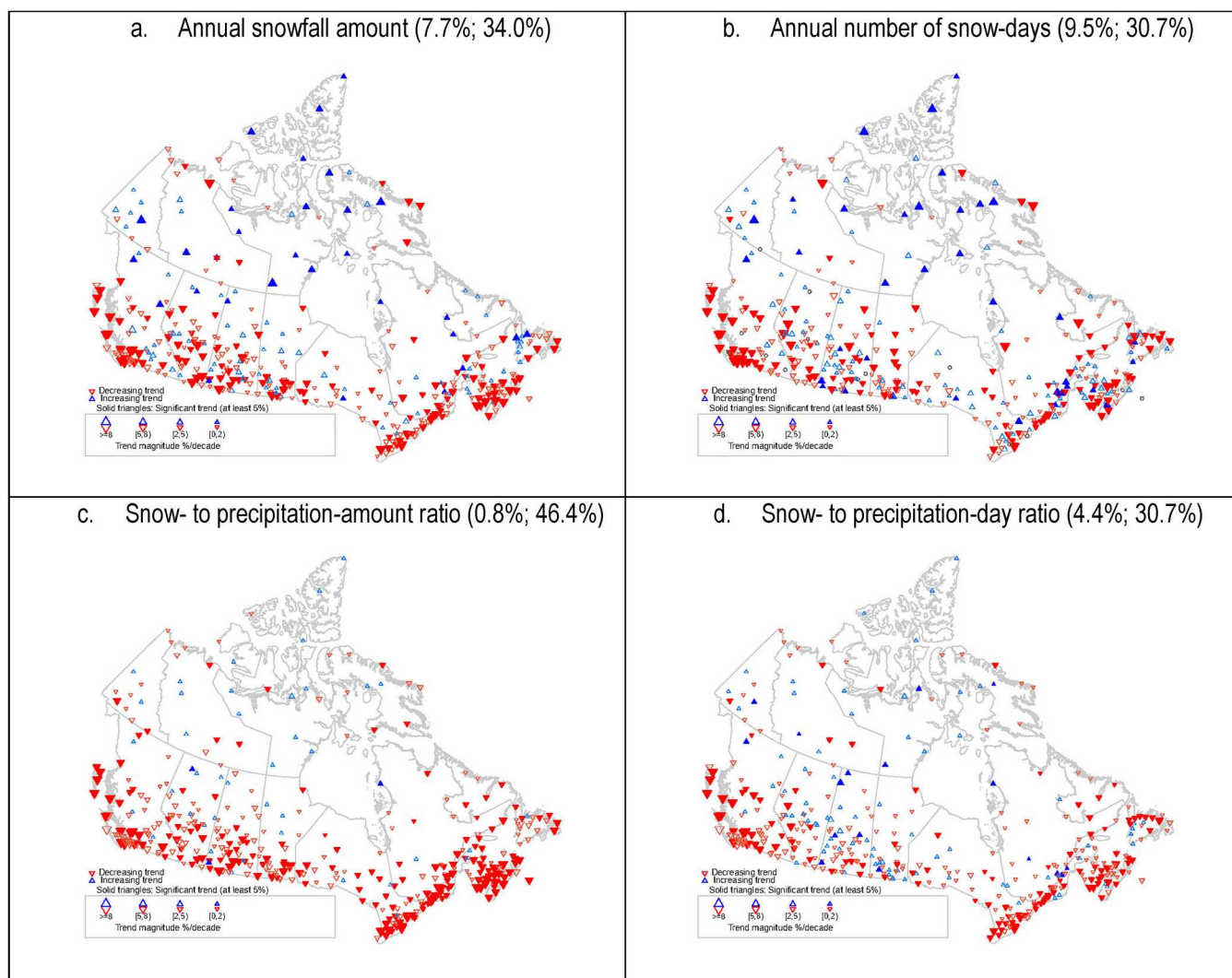


Fig. 6 Trends in annual snowfall amount, number of snow-days, proportion of precipitation amount falling as snow (snow- to precipitation-amount ratio), and proportion of precipitation days with snow (snow- to precipitation-day ratio) over the period 1949–2023 based on proxy snowfall estimates. The trends are expressed in percentage change per decade relative to the baseline (1961–1990) mean. Linear trends and the statistical significances were computed using the Mann-Kendall non-parametric estimator of Wang and Swail (2001). A snow-day is a day with snowfall water equivalent  $> 1.0$  mm, and a precipitation-day, a day with precipitation  $> 1.0$  mm. The numbers in parentheses are the percentages of stations with a significant positive trend and a negative trend at the significance level of 0.05.

indices including snowfall amount from the proxy daily snowfall series and investigate long-term trends in these snowfall indices. Our results show that the single temperature threshold method can accurately estimate annual and seasonal snowfall indices, especially when station-specific thresholds can be calibrated and applied, and that trends in these indices are in generally good agreement with the trends estimated from observed snowfall data. These results indicate that such simple methods can be applied to long-term homogenized precipitation and temperature data to investigate long-term changes in snowfall when long-term observed snowfall data are not available, as is the case in Canada at many automated stations.

It should be noted, however, that estimating daily snowfall and rainfall amounts from available temperature and precipitation data was not specifically our objective and that daily

snowfall amounts derived from partitioning might not be suitable for purposes other than estimating annual and seasonal snowfall amount and other related snowfall indices. The station-specific temperature thresholds calibrated in this study may also not be well applicable in other applications. For example, the single temperature threshold methods assign daily precipitation entirely to snowfall or rainfall, thus they cannot separate daily precipitation with mixed precipitation types. Existing dual-threshold methods using two temperature thresholds  $T_s$  and  $T_r$  with a smooth transition between these thresholds could be useful, particularly if sub-daily temperature data are available. Two threshold methods with a linear transition have been used in eastern Canada to simulate snow cover (Bélanger et al., 2002; Jégo et al., 2014), and with an S-shaped transition curve in Alberta (Kienzle, 2008).

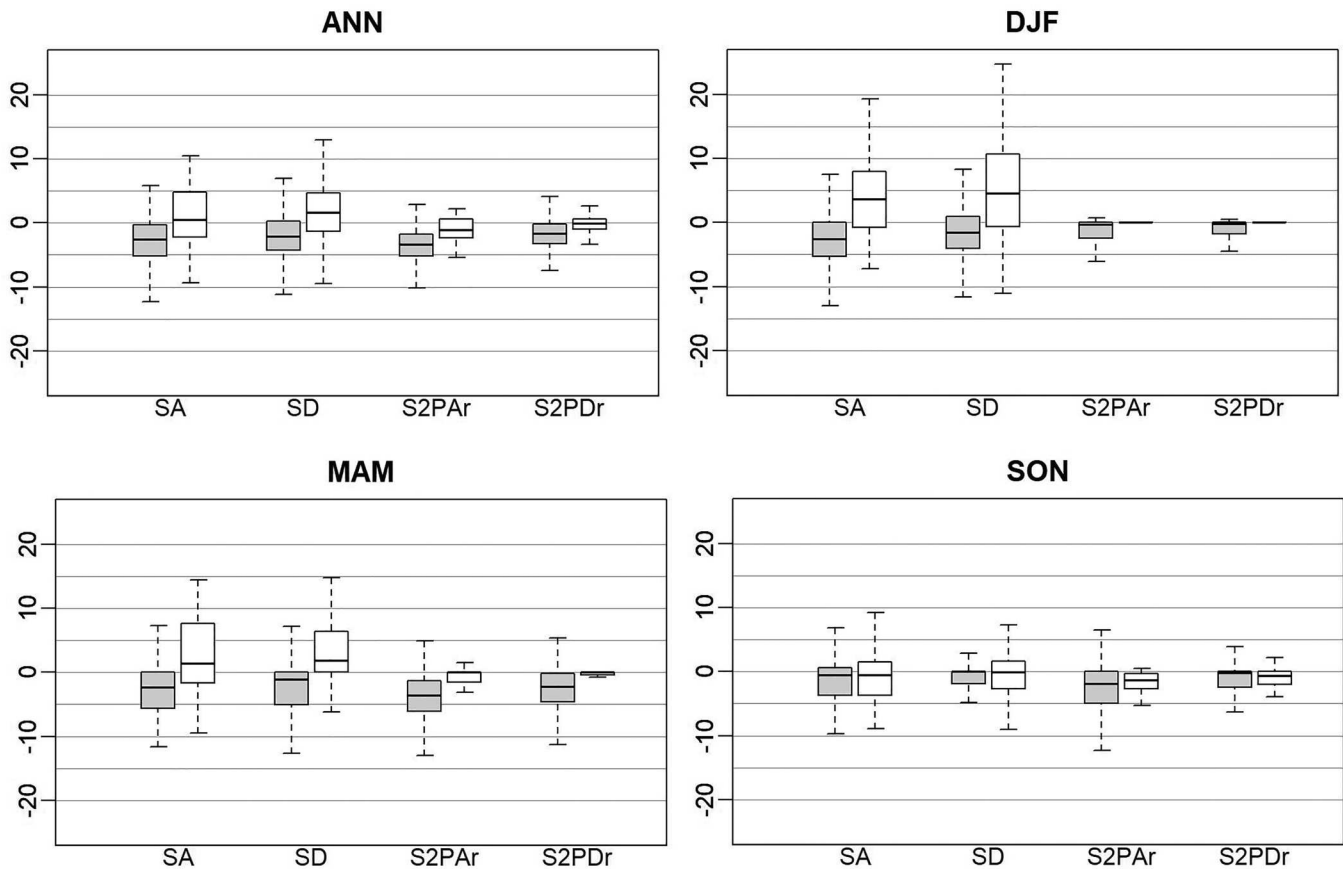


Fig. 7 Boxplots of trend magnitudes (% per decade) across the southern stations (south of 60°N, filled) and the northern stations (north of 60°N, unfilled) estimated for annual and seasonal snowfall amount (SA), number of snow-days (SWE > 1.0 mm) (SD), snow- to precipitation-amount ratio (S2PAr) and snow- to precipitation-day ratio (S2PDr) over the period 1949–2023. The trends are expressed in percentage of the baseline (1961–1990) mean. The boxes show the lower and upper quantiles with the median (horizontal line). The whiskers show the minimum and the maximum values excluding outliers. ANN: annual, SON: September–October–November, DJF: December–January–February, MAM: March–April–May.

TABLE 5. Median magnitude\* (% per decade) of the trends across the southern stations (south of 60°N) (values in brackets for stations north of 60°N) in annual and seasonal snowfall amount (SA), number of snow-days (SWE > 1.0 mm) (SD), snow- to precipitation-amount ratio (S2PAr), snow- to precipitation-day ratio (S2PDr) over the period of 1949–2023.

Indices	SA	SD	S2PAr	S2PDr
annual	−2.5 (0.5)	−2.1 (1.6)	−3.4 (−1.1)	−1.7 (−0.1)
SON	−0.6 (−0.6)	0.0 (−0.1)	−1.9 (−1.3)	−0.3 (−0.7)
DJF	−2.6 (3.6)	−1.6 (4.5)	−0.3 (0.0)	−0.2 (0.0)
MAM	−2.3 (1.4)	−1.1 (1.9)	−3.6 (0.0)	−2.3 (0.0)

\*Relative to the 1961–1990 mean at each station. SON: September–October–November; DJF: December–January–February; MAM: March–April–May. JJA (June–July–August) was excluded as snowfall does not occur in the summer months in most years, especially in southern Canada.

#### 4 Conclusions

We find that the simple T<sub>mean</sub> < 0°C can provide an effective proxy for daily snowfall for stations across Canada that can be used to derive snowfall indicators, including annual and seasonal snowfall amount (SA), number of snow-days (SD), snow- to precipitation-day ratio (S2PDr), and snow- to

precipitation amount ratio (S2PAr), which are informative of snowfall changes in Canada. The accuracy of snowfall indices derived from proxy daily snowfall data is often good, especially for annual and winter indices. The trends estimated from proxy snowfall indices well match those estimated from observed snowfall data in regard with their signs, magnitudes and statistical significance. The accuracy of annual and seasonal values of the snowfall indices is significantly improved when station-specific temperature thresholds are used, although the trend estimates are only marginally better in matching the observed trends than the T<sub>m0</sub> method.

Trends obtained from proxy snowfall data by applying the evaluated partitioning method to homogenized daily precipitation and temperature data show contrasting changes in annual snowfall amount between southern and northern stations, with a median trend of −2.5 and +0.5% per decade respectively, for the period 1949–2023. A similar contrast is also seen for annual number of snow-days (−2.1 vs. 1.6% per decade). A negative median trend in seasonal snowfall amount is found for winter and spring at southern stations while a positive trend is found at northern stations. A zero median trend in winter and spring proportions of snowfall

amounts to total precipitation and snow-days to precipitation days at northern stations implies that precipitation remains in the form of snow, which means that increasing precipitation there is mainly seen as increasing snowfall in these seasons. A higher decreasing rate is often seen in winter and spring at southern stations. Changes in snowfall should be regularly re-assessed in a changing climate, especially for northern Canada where continued warming might eventually result in changes in the form of precipitation. The simple precipitation partition method in this study might be useful for this purpose.

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### Supplemental data

Supplemental data for this article can be accessed at <https://doi.org/10.1080/07055900.2025.2586566>

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