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A new temperature based method to separate rain and snow

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Abstract:

This paper presents the development and testing of a new method to estimate daily snowfall from precipitation and associated temperature records. The new method requires two variables; the threshold mean daily air temperature at which 50% of precipitation is considered snow, and the temperature range within which mixed precipitation can occur. Sensitivity analyses using 15 climate stations across south-western Alberta, Canada, and ranging from prairie to alpine regions investigates the sensitivity of those two variables on mean annual snowfall (MAS), the coefficient of determination, and the MAS-weighted coefficient of determination. Existing methods, including the static threshold method, one linear transition method used by Quick and Pipes, and the Leavesley method employed in the PRMS hydrological modelling system are compared with the new method, using a total of 963 years of daily data from the 15 climate stations used for the sensitivity analyses. Four different approaches to using the two input variables (threshold temperature and range) were tested and statistically compared: mean annual variables based on the 15 stations, mean annual variables for each station, mean monthly variables for each station, and a sine curve representing seasonal variation of the variables. In almost all cases the proposed new method resulted in higher MAS-weighted coefficients of determination, and, on average, they were significantly different from those of other methods. The paper concludes with a decision tree to help decide which method and approach to apply under a variety of data availabilities. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS precipitation separation; snow; rain; mean annual snowfall; sensitivity analysis; model intercomparison analysis

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INTRODUCTION

Water balance calculations in cold climates require the separation of precipitation into snow and rain. This separation is critical to determine whether water is available for runoff and soil infiltration, or if it is stored as snow. Alberta's water resources, in line with other locations along the eastern slopes of the Rocky Mountains, depend profoundly on the accumulated snowpack in the foothills and, in particular, the alpine regions. Snow accumulated in the prairies can also be of significance for soil moisture budgeting and occasional aggravation of flood events. Due to projected water shortages in south-western Alberta (Byrne *et al.*, 1999; Lapp *et al.*, 2002, 2005; Rood *et al.*, 2005) and the subsequent need for reliable hydrological models to predict future scenarios, it is essential to model the incoming snow volumes and their seasonal behaviour realistically.

The main factors determining whether precipitation falls as rain or snow are the thickness and temperature of the atmospheric layers (Gray and Prowse, 1993), with the zero degree boundary layer being the dominant determinant (Grebner, 1978 in Braun, 1985). Other meteorological conditions may also play a role, such as type of clouds, air mass movement and humidity. Most weather stations measure and report the water equivalent of precipitation without specifying whether it is rain or snow (Dingman, 2002). Even in regions such as Alberta, where rain and snow are recorded separately, the records can typically not be directly used for hydrological simulations. This is due to the distribution of the climate stations, which are, as everywhere else in the world, situated for ease of access rather than to represent the full range of elevations and associated climatic conditions. This results in a bias towards representing lower elevations, particularly in regions with high relief. The consequences are that the snow to rain proportions observed at the climate stations cannot be transferred to locations with distinctly different elevations. Therefore, the air temperature measured near the ground is generally used as the determining factor for the partition of precipitation into snow, mixed precipitation, or rain (Rachner and Matthäus, 1984; Braun, 1985; Vehviläinen. 1992; Rachner *et al.*,1997). When temperature values are required where no measurements are available, lapse rates are commonly used to adjust the minimum and maximum temperatures measured at the nearest climate stations to the location under consideration. An environmental temperature lapse rate of 6·5 °C km^{-1} is often used when no local information is available. However, this theoretical environmental lapse rate may not be applicable in mountainous regions, because of the variability of topographical influences on meteorological elements such as temperature, precipitation, wind speed, and solar radiation (Rolland, 2003). Mean annual lapse rates in the latitudes of this study range from 5·4 to 6·9 °C km^{-1}, and in addition, there is a seasonal variation, with summers having the highest lapse rates (Pigeon and Jiskoot, in press).

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The temperature based approach could, in the future, be replaced by coupling hydrological with atmospheric models, which could directly provide the type of precipitation. There is considerable global research effort to couple hydrological with atmospheric models, such as the Canadian MESH model (Pietroniro *et al.*, 2007). A major problem with atmospheric models remains that their spatial resolution is coarse, typically square cells several 100 km^2 in size, and that downscaling methods from regional to local scale still struggle to provide proper representation in terrain with high relief.

The Oldman River Watershed includes alpine areas, with approx. 10% of the watershed area with elevations between 1750 and 3150 m. The transitional foothills region is roughly associated with an elevation range from 1200 to 1750 m and makes up about 30% of the Oldman River Watershed. Following to the east are the prairies. The mean annual precipitation decreases from over 750 mm yr^{-1} in the west to under 400 mm yr^{-1} in the east. Daily temperature ranges are very large due to the continental climate and the frequent occurrences of warm fall winds, which are called Chinook, meaning 'Snow Eater' in Blackfoot First Nation language. The wide range of daily mean temperature associated with snowfall is demonstrated at a climate station in Claresholm, where snowfall over 5 mm snow water equivalent (SWE) has been observed within a daily mean temperature range of 45 °C, from -31 to $+14$ °C (Figure 1). Likewise, Sevruk (1984) reports a large variability of the relative precipitation proportions near 0 °C and determined that, for his Swiss study area, only 68% of the variability of the snow proportion can be explained by temperature alone.

Lauscher (1982, in Braun, 1985) reports high variability of the transition from solid to liquid precipitation in the Vienna region of Austria. He determined snowfall to occur below a mean temperature of 1·74 °C, with a standard deviation of 1·5 °C. He also determined a seasonal variation of the threshold temperature, with a lowest mean threshold temperature in January of 1·4 °C and a highest in April of 2·6 °C.

Several researchers have developed relationships between temperature and the probability of snow. Auer (1974) used the average of 1000 observations across the USA to develop a temperature dependent snow probability curve (Figure 2). Auer further reported that rain was virtually never recorded when the temperature was less than 0 °C and snow was never observed when the temperature exceeded 6·1 °C. Yang *et al.* (1997) applied the 2·2 °C division temperature, which corresponds to the 50% probability of snow from the Auer curve, in the former Soviet Union. Others, such as Lynch-Stieglitz (1994) and Motoyama (1990), used 0 °C as the snow–rain threshold temperature. Motoyama (1990) applied different threshold temperatures for two locations studied in Japan: 0 °C for Hokkaido and temperatures between 1° and 3 °C in Honshu. Loth *et al.* (1993) tested several threshold temperatures for their snow cover simulations in Davos, Switzerland. They tested threshold temperatures of 0°, 1° and 2 °C and concluded that different thresholds, together with the occurrence of mixed precipitation, influenced the snowpack properties in terms of depth and snow water equivalent. Rohrer (1989) reported two similarly shaped curves for Davos and Arosa in Switzerland, and further distinguished between summer and winter (Figure 3). L'Hote *et al.* (2005) report S-shaped transition curves for both the Swiss Alps and the Bolivian Andes. It is interesting to note that they report very similar threshold temperature and temperature ranges for the two alpine areas (Figure 3). Their curve for the Alps is very similar to the one reported by Rohrer (1989).

Fassnacht and Soulis (2002) fit a sixth-order polynomial to the Auer (1974) and other data, with upper and lower temperature limits to restrict the polynomial curve, which has a range of 6°. Braun (1985) reported a temperature range observed in Switzerland from +4·0 to -2·0 °C where a rain–snow mix can occur. Vehviläinen (1992) used a gradual threshold temperature in his low-relief Finnish study area, with a 90% snow proportion at -1·2 °C, a 75% snow proportion at 0 °C, and a 50%

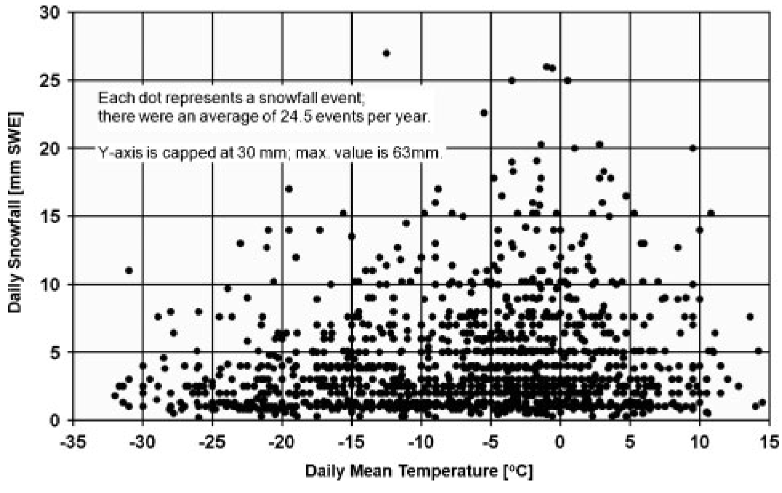

Figure 1. Snowfall in the foothills of southern Alberta can occur over a very wide range of mean daily temperatures due to the continental climate and regular occurrence of strong fall winds (Chinook) during winter; the climate station is at Claresholm, Alberta, Canada

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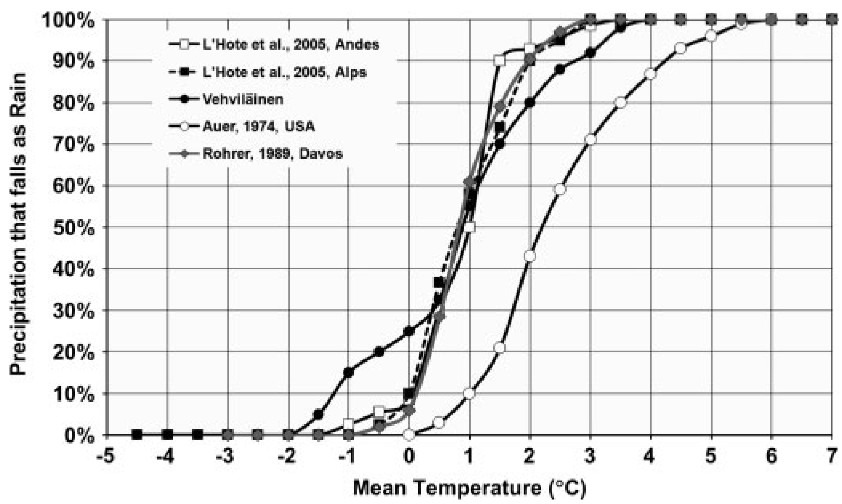

Figure 2. Several mean snow proportion curves developed for different locations

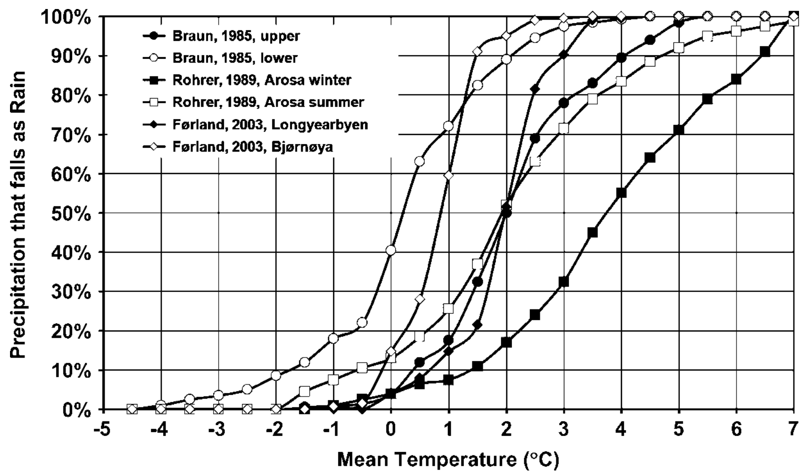

Figure 3. Reported snow proportion curves with a wide range due to location or seasonal differences

snow proportion at 0·9 °C (Figure 2). These observations suggest that a dynamic temperature approach is required to determine the precipitation type.

There are currently three different approaches available to separate precipitation into rain and snow based on air temperature (Figure 4). One type of approach uses the static threshold temperature method. Based on this method, 100% of snowfall is assumed when temperatures are below the threshold temperature, otherwise 100% rainfall is assumed. This static threshold method is used in the Swedish HBV model (Bergström, 1995), the Snowmelt Runoff Model (Rango, 1995), or the SLURP model (Kite, 1995). Another approach uses a gradual change of the proportion of rain and snow based on a linear transition over several degrees, such as the Canadian UBC Watershed Model (Pipes and Quick, 1977). The Pipes and Quick method uses the following equation:

for $T \leq 0{\cdot}6\,^{\circ}\mathrm{C}$: all precipitation is considered snow

for $T > 0{\cdot}6\,^{\circ}\mathrm{C}$ and $T < 3{\cdot}6\,^{\circ}\mathrm{C}$:

$$\text{rain proportion} = (T/3) - 0{\cdot}2 \qquad (1)$$

for $T \geq 3{\cdot}6\,^{\circ}\mathrm{C}$: all precipitation is considered rain

where T = mean daily air temperature near ground level, in °C.

Others, such as the US Army Corps of Engineers (USCE, 1956) or Braun (1985) use slightly different linear equations. A third approach, applied in USGS's PRMS model (Leavesley *et al.*, 1983), is more complex. Here, the snow proportion is a function of daily minimum and maximum temperatures. If the minimum temperature is larger than the threshold temperature, then all precipitation is considered rain. If the maximum temperature is smaller than the threshold temperature, then the precipitation is considered to fall as snow. When the threshold temperature is between the minimum and maximum temperature, the rain proportion of the mixed precipitation is calculated by dividing the difference between maximum and threshold temperature by the difference between the minimum and maximum temperatures, and adjusting the product by a monthly correction factor. In addition, a second threshold temperature can be defined where all precipitation is regarded as rain, irrespective of the daily maximum temperature. A fourth method is proposed here, which uses an S-shaped curve instead of a linear transition. The shape of the curve is determined by

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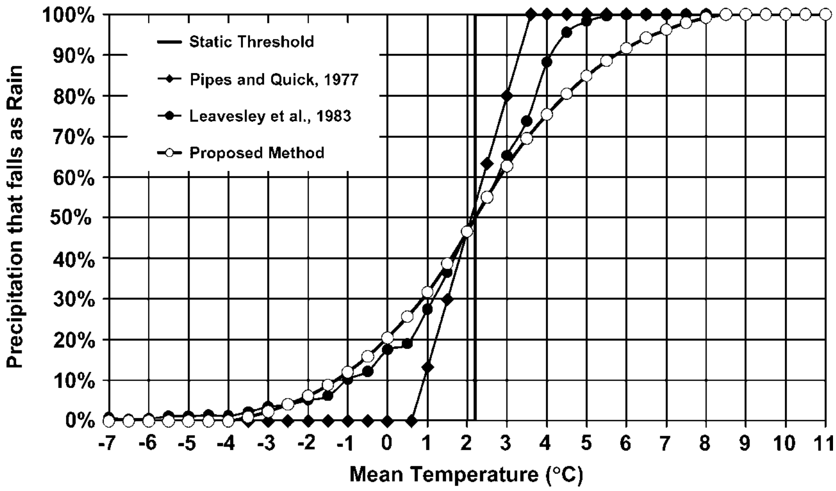

Figure 4. Four functions to determine the proportion of precipitation that falls as rain as a function of mean daily ground air temperature. All, except Pipes and Quick, are based on a threshold temperature of 2·2 °C. The Leavesley *et al.* curve is an example based on climate data from Beaver Mines in southern Alberta; every climate station would result in an individual curve. The example curve for the proposed method uses a temperature range of 13 °C, common for southern Alberta

the threshold temperature and the range of temperatures.

It has been previously shown that the proportion of precipitation that falls as snow varies in different regions, often within those regions, and also throughout the year. This can severely hamper hydrological simulations in cold climates. As observations worldwide show a rather curvilinear change from rain to snow with air temperature (Figures 2 and 3), linear relationships appear to be too simplistic.

The objective of this study was to investigate the shape of the snow-to-rain proportion as a function of daily mean air temperature for south-western Alberta. The mathematical formulation of an S-shaped curve for snow modelling was proposed. The sensitivity of the two input variables describing the curve of mean annual snowfall and other objective functions was tested. A number of comparative analyses were carried out to both test the proposed method against observed data and compare the results against several existing methods. The seasonal behaviour of the snow-to-rain proportion was investigated and an attempt was made to derive generic equations to represent the seasonal behaviour. Finally, based on the findings, a decision tree was constructed to recommend a universal approach to improve the snowfall estimations from precipitation records.

SNOW PROPORTIONS OF PRECIPITATION IN SOUTH-WESTERN ALBERTA

Rain and snow measurements

Daily precipitation observations were derived from the National Data Archive, Meteorological Service of Canada, Environment Canada. In Canada, rain is measured using the standard Canadian rain gauge, a cylindrical container, 40 cm high and 11·3 cm in diameter (Devine and Mekis, 2008), measuring in 0·2 mm increments. Rainfall measurements in Canada are known to undercatch rain by over 7% (Metcalf *et al.*, 1996), due to systematic errors such as wetting loss, wind effects and trace precipitation, or non-systematic errors such as human recording errors and local positioning of the gauge. At approximately 95% of climate stations that measure snowfall, snowfall is measured as the depth of newly fallen snow at several locations near the gauge, measured using a snow ruler to the nearest 2 mm. All stations used in this study are so-called Ordinary Stations, where the measured snow depth is converted to snow water equivalent by dividing the depth by ten, assuming a snow depth to water ratio of 1 : 10. This method works generally quite well, but it has the potential for severely over- or under-estimating the true snow water equivalent, as the density of falling snow can vary by a large degree. As air temperature and humidity affect the density of falling snow, relatively warm and humid conditions will result in high-density, heavy, often termed 'wet', snow, while cold and dry conditions will result in low-density snow. Based on empirical research, Dunn and Colohan (1999) reported the range of the density of freshly fallen snow to be between 0·05 and 0·3 g cm^{-1}. Accordingly, the simple method applied for ordinary climate stations can be over-estimating the snow water equivalent by 100%, or under-estimating it by 300%. Goodison and Metcalfe (1981) measured the fresh snowfall water equivalent at selected Canadian stations over a 3 year period and reported that seasonal average fresh snowfall densities ranged from 0·070 to 0·165 g cm^{-3} across Canada, with an average value of 0·071 to 0·084 g cm^{-3}. This would result in an approximately 20% over-estimation of snowfall when one uses the simple 1 : 10 ratio between snow density and snow water equivalent.

The Canadian Nipher Shielded Snow Gauge System is the standard instrument for measuring snowfall amount as water equivalent, and is used only at so-called Principal Stations. A WMO Intercomparison Study (1992) indicated that the catch of the Canadian Nipher Shielded Gauge is very similar to the WMO reference standard (Goodison and Metcalfe, 1992).

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Table I. Information on climate stations used for the sensitivity and model intercomparison analyses. Stations are sorted by the precipitation proportion that falls as snow

Station	Station ID	Years of observation (rounded)	Elevation [m]	MAP [mm]	Precipitation as snow [%]
Strathmore	2309	40	963	416	20·2
Foremost	2240	64	892	404	21·9
Gleichen	2247	97	905	370	26·3
Claresholm Waterworks	2227	46	1008	437	29·1
Lethbridge CDA	2265	88	921	400	30·8
Fort Macleod	2243	86	950	415	30·9
High River	2255	96	1219	501	35·4
Cardston	2211	79	1193	508	36·7
Coleman	2381	82	1341	549	38·1
Pekisko	2427	45	1439	653	42·6
Carway	2219	90	1354	520	46·5
Beaver Mines	2366	92	1257	630	47·2
Fording River Comino	1184	32	1585	651	49·5
Fording River Clode Creek	1183	9	2100	747	56·2
Natal Harmer Ridge	1203	17	1890	729	65·8

The study area, which basically covers the Oldman River watershed and some climate stations in its direct vicinity, contains no climate stations where the Canadian Nipher Shielded Snow Gauge System is used. The rain and snow measurements contained in the National Data Archive were used unaltered, and the data were not corrected in any way. Goodison (1981) states that the ruler method based on the 1 : 10 ratio is inconsistent and unreliable for short-term analysis. However, due to the long records of most stations used in this study, an average of 64 years (Table I), the average annual snowfall would have a reduced error, as over- and under-estimations of snow water equivalent could be cancelled out to a significant degree.

Analysis of snow proportions

Daily precipitation data from 113 climate stations in south-western Alberta and south-eastern British Columbia were analysed for their snow proportions at varying air temperatures. 92 stations (81% of stations investigated) exhibited an s-shaped curve when all available values were considered. Those stations that did not exhibit a clear s-shaped curve have relatively short records with less than a total of 500 precipitation observations (the mean number of observed precipitation days for the 113 stations is 2216). From the 113 climate stations, 15 were selected for sensitivity and model intercomparison analyses, based on record length and spatial representation within south-western Alberta. The mean number of observed precipitation days for the 15 stations is 5300. Figure 5 shows the locations of the 113 climate stations and the selected stations, which are labelled with their Environment Canada Station ID. Figure 6 presents examples of the temperature–snow proportion relationships for six stations.

Based on these observations, a curvilinear method is proposed that can be calibrated based on snow observation at local stations, with the two key variables being the threshold mean daily temperature (T_T), where 50% snowfall occurs, and the range of temperatures (T_R) within which both solid and liquid precipitation occurs. This means that the curve can be both stretched along the x-axis by increasing the T_R variable, and moved along the x-axis by changing the T_T variable, according to observations or calibration at a specific location:

$$\begin{aligned}
&\text{for } T \leq T_T \text{ and } P_{Rain} \geq 0: \\
&P_{Rain} = 5 \times \left(\frac{T - T_T}{1{\cdot}4 \times T_R}\right)^3 + 6{\cdot}76 \times \left(\frac{T - T_T}{1{\cdot}4 \times T_R}\right)^2 + 3{\cdot}19 \times \left(\frac{T - T_T}{1{\cdot}4 \times T_R}\right) + 0{\cdot}5 \\
&\text{for } T \geq T_T \text{ and } P_{Rain} \leq 1: \\
&P_{Rain} = 5 \times \left(\frac{T - T_T}{1{\cdot}4 \times T_R}\right)^3 - 6{\cdot}76 \times \left(\frac{T - T_T}{1{\cdot}4 \times T_R}\right)^2 + 3{\cdot}19 \times \left(\frac{T - T_T}{1{\cdot}4 \times T_R}\right) + 0{\cdot}5
\end{aligned} \tag{2}$$

where P_{Rain} is the proportion of precipitation falling as rain, ranging from 0 to 1; T is mean daily air temperature near ground level, in °C; T_T is threshold temperature, where 50% of precipitation falls as rain, in °C, typically around 2 °C; T_R is range of temperatures where both rainfall and snowfall can occur, in °C, typically around 13 °C.

Figure 6 shows both the observed snow and rain proportions and the fitted curves for six of the 15 stations investigated in south-western Alberta. The first three

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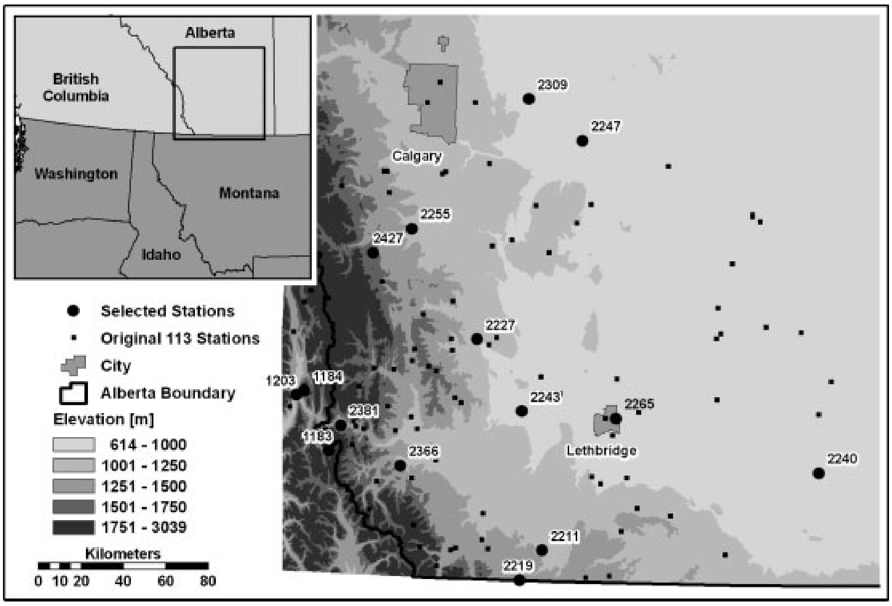

Figure 5. Location of climate stations used in the study

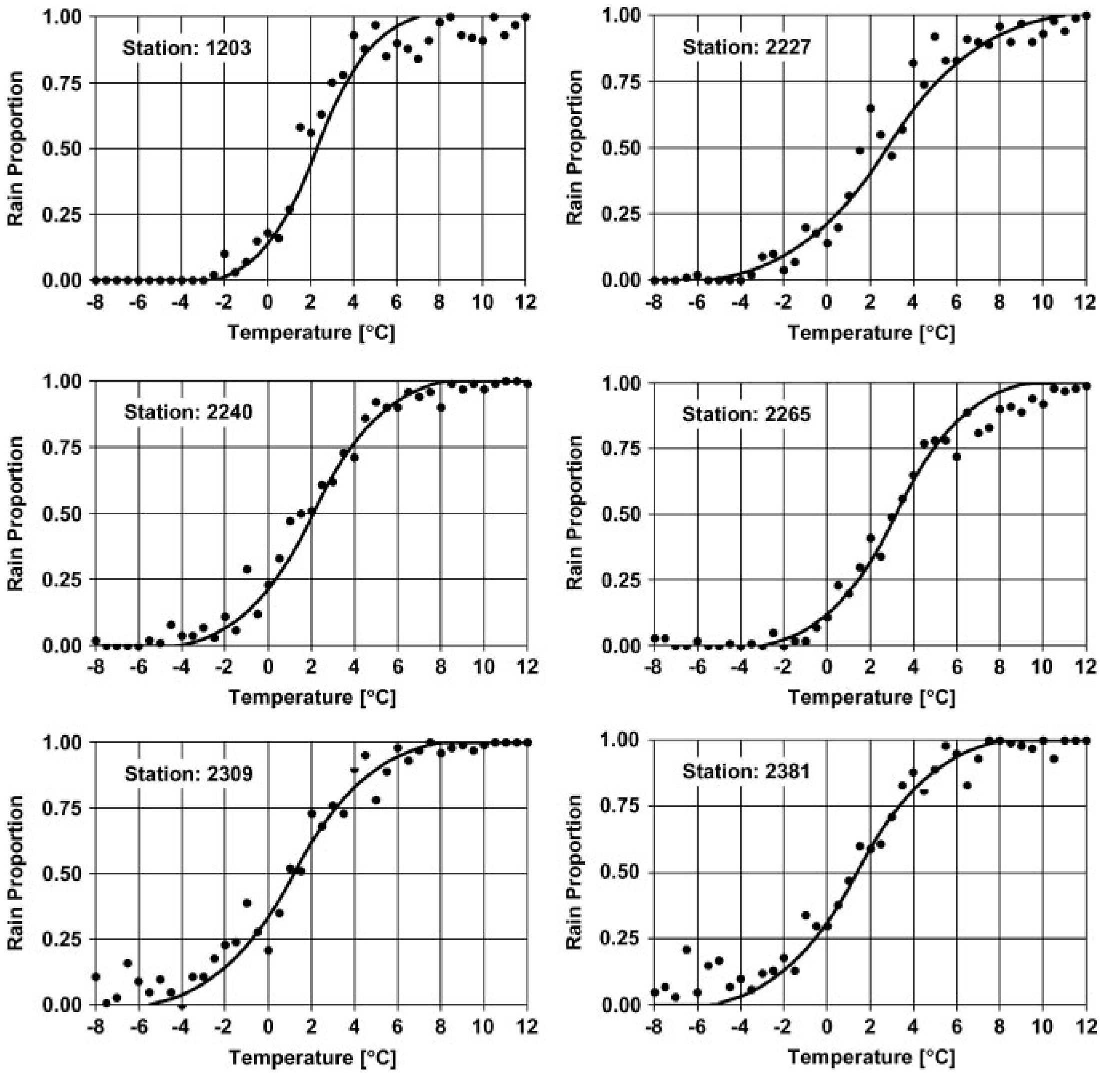

Figure 6. Snow and rain proportions versus daily mean temperature for six stations in south-west Alberta, with respective curvilinear fits

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graphs in Figure 6 show the climate stations where the fitted curves exhibit the highest coefficients of determination, with r^2 values of 0·94 at Station 1203, 0·85 at Station 2227, and 0·82 at Station 2240. The other three graphs present climate stations with the lowest r^2 values, which were 0·75, 0·73 and 0·72, respectively, for stations 2265, 2381 and 2309. A visual inspection of the various curves suggests that the threshold temperature, associated with the 50% snow or rain proportion, can vary from approx. 1·5 °C at Station 2309 to approx. 3·5 °C at Station 2265. Also evident from Figure 6 is that the spread around the threshold temperature is variable, and can be much larger than the 6° range reported by Fassnacht *et al.* (2001) or Braun (1985). Based on the figures provided, a range from about 10 °C at Station 1203 to about 18 °C at Station 2227 can be observed.

SENSITIVITY ANALYSES

A sensitivity analysis of the two input variables, T_T and T_R, was carried out for 15 climate stations in southern Alberta. From the 113 climate stations available for the Oldman River Watershed in south-western Alberta, 15 climate stations were selected on the basis of record length, spatial distribution, elevation and proportion of precipitation that falls as snow (Table I). Only two stations out of the selected 15 stations have a daily observation record of less than 30 years, but they were included to represent high elevation measurements and locations with a high proportion of snowfall. Altogether 963 years of daily observations were used. Between nine and 96 years of daily observations were available for each station. The selected climate stations have elevations ranging from 892 m in the prairies to 2100 m in the Rocky Mountains. Associated with the elevations is the proportion of precipitation falling as snowfall, ranging from about 20% in the prairies to a maximum of 65% in the alpine area. The stations are spatially quite evenly distributed across south-western Alberta and the very south-eastern corner of British Columbia (Figure 5).

Three objective functions were used to evaluate the sensitivity of T_T on snowfall estimations. The first objective function is the preservation of mean annual snowfall, as this is critical for the successful simulation of snow packs to estimate the total input into a watershed correctly. Mean annual snowfall was computed by summing up all available daily snowfall observations and dividing the sum by the number of years of observation, which could be a fraction. The impact of the change of T_T to the annual snowfall is expressed in percent change, δ, relative to the observed mean annual snowfall of the respective climate station:

$$\text{for under-estimations of MAS}: \delta = (MAS_{est}/MAS_{obs}) \times 100$$

$$\text{for over-estimations of MAS}: \delta = (MAS_{obs}/MAS_{est}) \times 100 \tag{3}$$

with MAS_{est} the estimated mean annual snowfall, and MAS_{obs} the observed mean annual snowfall.

The second objective function is the coefficient of determination, used here to assess the intra-annual variation of estimated snowfall. As the coefficient of determination (r^2) is based on the squared differences between estimated and observed values, it is well suited, as it is particularly important to estimate the large snow fall events correctly:

$$r^2 = \Sigma\frac{(S_{obs} - \overline{S_{obs}})^2 - \Sigma(S_{obs} - S_{est})^2}{\Sigma(S_{obs} - \overline{S_{obs}})^2} \tag{4}$$

where S_{obs} is the daily observed snowfall value, $\overline{S_{obs}}$ is the mean value of observed snowfall, and S_{est} is the estimated daily snowfall.

In order to assist further in the assessment of the overall sensitivity of the threshold temperatures on the estimation of the snow proportion and provide a more comprehensive reflection of estimation results, an efficiency measure is used as a third objective function that combines the two objective functions into one weighted function (δr^2):

$$\text{for under-estimations of MAS}: \quad \delta r^2 = r^2 \times (MAS_{est}/MAS_{obs})$$

$$\text{for over-estimations of MAS}: \quad \delta r^2 = r^2 \times (MAS_{obs}/MAS_{est}) \tag{5}$$

For the assessment of the sensitivity of estimations of daily snow fall from mean daily air temperature for each of the 15 climate stations, T_T was incremented by half a degree ranging from 0 °C to 5·5 °C, while T_R was kept static at 13 °C, which is the median value observed at the stations investigated.

The sensitivity of the temperature range on the estimation of snowfall was tested by incrementing the temperature range between 0 and 22 °C, with 2 °C increments, while applying the best threshold temperature resulting from the sensitivity analysis of T_T, using the δr^2 measure for each station.

Results of the sensitivity analysis of the threshold temperature

Results of the sensitivity analysis for T_T are displayed in Figures 7 to 9. Results displayed in Figure 7 show that the estimation of mean annual snowfall for the 15 stations reveal a similar sensitivity to one another. On average, each degree difference in the threshold temperature (in °C) results in a change in estimated mean annual snowfall of 8·7%. The most insensitive station (Station 1203) also has one of the highest elevations with the largest snowfall proportion and exhibits an average 4·8% change in estimated snowfall per degree change of T_T. The most sensitive station is Station 2265, which has one of the lowest elevations and changes by 10·8% per degree change of T_T. This station also has the highest threshold temperature at which the mean annual snowfall is estimated perfectly, displayed in Figure 7 as black

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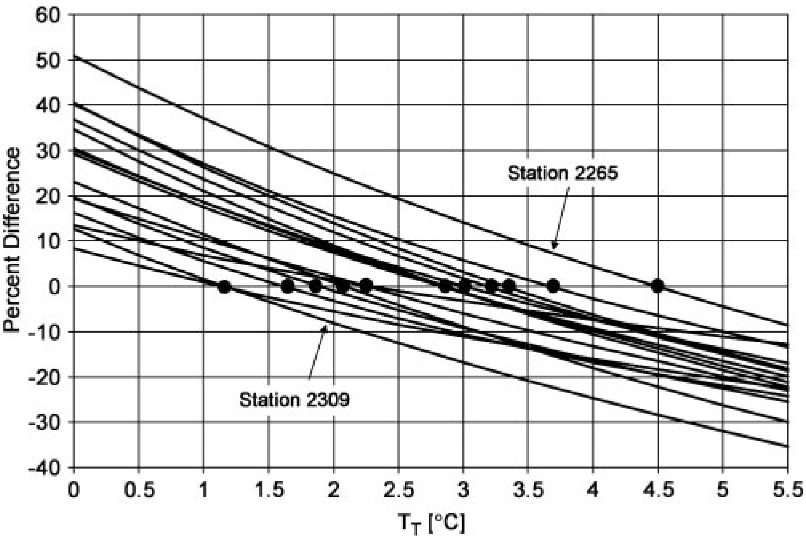

Figure 7. First objective function for sensitivity analysis of T_T: The effect of the change of T_T on the percentage change of estimated mean annual snowfall. The black dots represent optimum threshold temperatures, with the two most extreme climate stations being labelled

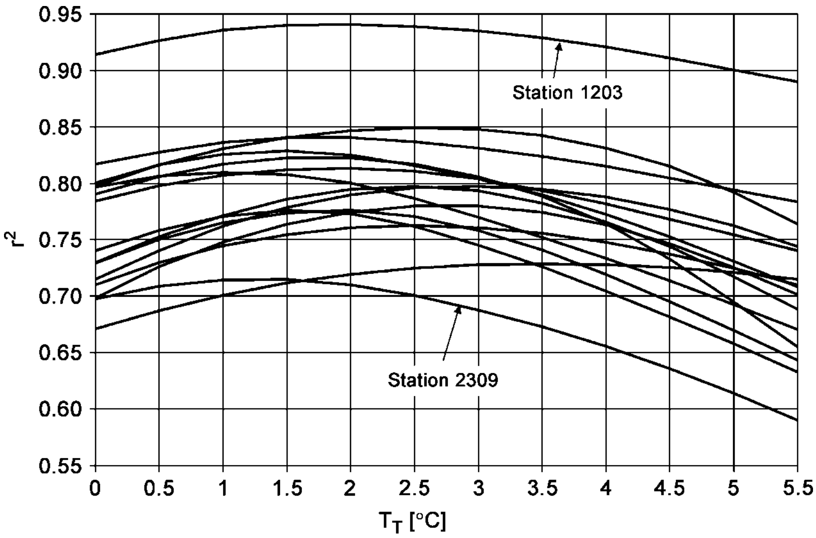

Figure 8. Second objective function for sensitivity analysis of T_T: the effect of the change of T_T on the coefficient of determination

dots, of 4·5 °C. Figure 7 also reveals the wide range of T_T values associated with a perfect mean annual snowfall estimation, which spreads from 1·2 to 4·5 °C. Also evident from this Figure is that the application of a static threshold temperature, for example 2·0 °C, can result in both significant under- or over-estimation of annual snowfall. The associated estimation error of mean annual snowfall can easily be 10% or more.

A change in the threshold temperature also affects the coefficient of determination (Figure 8). The average sensitivity is quite low, with a mean r^2 change of 0·029 per degree change in the threshold temperature. The largest change in r^2 is 0·052 per degree change in the threshold temperature, and the lowest is 0·015. The threshold temperatures associated with the highest r^2 do not necessarily coincide with those associated with the best estimation of mean annual snowfall. In some cases, such as Station 1203, the best threshold temperature for the two objective functions is the same. However, some stations reveal a difference in the optimum threshold temperature, based on the two objective functions, of up to 2 °C, such as Stations 2265, 2255 and 2381.

Results for the combined efficiency measure are displayed in Figure 9. The Figure displays clear peaks, which, in 12 out of 15 cases, coincide with the optimum estimation points of mean annual snowfall (black dots) shown in Figure 7. In the three cases where the two optimum threshold temperatures associated with the two objective functions differ, the difference is small with 0·5 °C.

Results of the sensitivity analysis of the temperature range

The sensitivity of the change of the temperature range on mean annual snowfall and the coefficient of determination are displayed in Table II. Results show that the change in T_R has little effect on the mean annual snowfall. Average changes of 0·11% per degree

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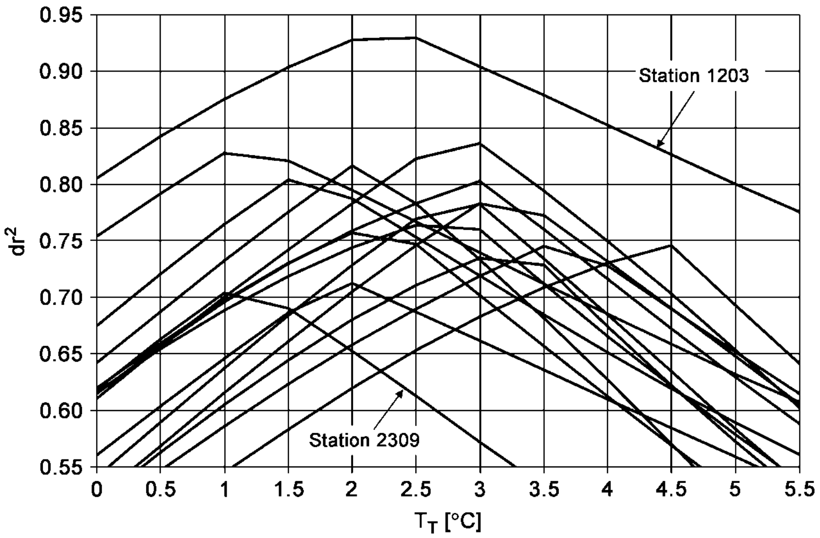

Figure 9. Third objective function for sensitivity analysis of T_T: The effect of the change of T_T on the MAS-weighted coefficient of determination

Table II. Results of the sensitivity analysis of the temperature range on snowfall estimations

Station	Station ID	Best T_T [°C]	Best T_R [°C]	Change in MAS per °C T_T [%]	Improvement of r^2 relative to zero range
Strathmore	2309	1·1	14	8·7	0·045
Foremost	2240	2·1	11	9·6	0·055
Gleichen	2247	2·3	10	7·7	0·069
Claresholm Waterworks	2227	2·8	11	9·4	0·048
Lethbridge CDA	2265	4·5	13	10·8	0·065
Fort Macleod	2243	3·2	15	10·1	0·055
High River	2255	2·8	15	8·9	0·094
Cardston	2211	3·3	12	10·7	0·065
Coleman	2381	1·9	15	8·2	0·055
Pekisko	2427	2·9	11	10·4	0·050
Carway	2219	3·0	13	8·6	0·078
Beaver Mines	2366	3·7	16	9·8	0·055
Fording River Comino	1184	1·6	17	7·4	0·097
Fording River Clode Creek	1183	1·1	16	5·6	0·110
Natal Harmer Ridge	1203	2·3	10	4·8	0·020
Mean	—	2·6	13·3	8·7	0·064
Median	—	2·8	13·0	8·9	0·055

increase in temperature range were observed, with a maximum rate of 0·24%. However, T_R does improve the intra-annual estimation of snowfall, as expressed by the coefficient of determination. As is evident from Figure 6, different climate stations reveal a different spread around the threshold temperature. This spread impacts the coefficient of determination. If one compares the T_R value of zero, which represents no gradual change of snow proportions with temperature and disregards mixed precipitation, with the temperature associated with the highest r^2, the improvements of estimates can be considerable. When one compares the coefficient of determination of estimates with a T_R of zero with estimates based on the best T_R, the average improvement is an increase in the r^2 value by 0·064, with the highest increase of 0·110 (Station 1183) and the lowest increase of 0·020 at Station 1203. The average T_R value associated with the highest r^2 value is 13·3 °C, with the smallest range of 10 °C observed at high elevation station 1203 and low elevation station 2247. The largest range was observed at station 1184, which has a relatively high elevation, of 17 °C.

Can the threshold temperatures and temperature range be estimated from elevation data?

The question arises whether T_T and T_R can be predicted using elevation as the independent variable. Correlation analyses between T_T and elevation revealed a poor relationship with an r^2 value of 0·158 (Figure 10). However, there is evidence that, in the study area, there is a general decrease in T_T with an increase in elevation. This can be attributed to the regular occurrences of warm Chinook fall winds. These winds can increase air temperatures by 20° or more within a few hours, resulting in unusually high mean daily temperatures. Consequently, a snowfall event occurring before the onset of the Chinook would be associated with a relatively high mean daily temperature. The region associated with the

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Chinook winds will also have the largest daily temperature range, which is likely the reason for a very high threshold temperature at Lethbridge (Station 2265). The relationship between elevation and T_R also reveals poor correlation, with an r^2 value of 0·055. It follows, that neither T_T nor T_R can be predicted with confidence from elevation data alone.

MODEL INTERCOMPARISON

The separation of precipitation into snow and rain was tested for the 15 climate stations used in the sensitivity analysis (Table I) using four different methods:

(a) the static threshold temperature method,
(b) the Leavesley *et al*. (1983) method,
(c) the Pipes and Quick (1977) method, and
(d) the proposed curvilinear method.

The four methods were tested under four conditions:

(a) using the same mean annual T_T and T_R values for all stations as listed in Table II;
(b) using the observed best annual T_T and T_R values for each station, as determined in the sensitivity analysis;
(c) using observed mean monthly T_T and T_R values for each station; and
(d) using a sine curve generically fitted to the mean monthly T_T and T_R values and adjusted for mean annual T_T and T_R values for all stations.

To assess the success of the simulations, only one objective function, the MAS-weighted coefficient of determination, is used. To show the relative successes of the different methods and conditions in estimating the mean annual snow, the respective over or under-estimations of the MAS are also tabled. Results are listed in Tables III to IX for each station. The two-tailed Wilcoxon Signed Ranks Test was applied to reveal if a significant difference exists between the test results based on the proposed method and the other three methods. The test statistic reported is based on the 5% significance level. If the test statistic is below 0·05, then a significant difference exists between the proposed method and the

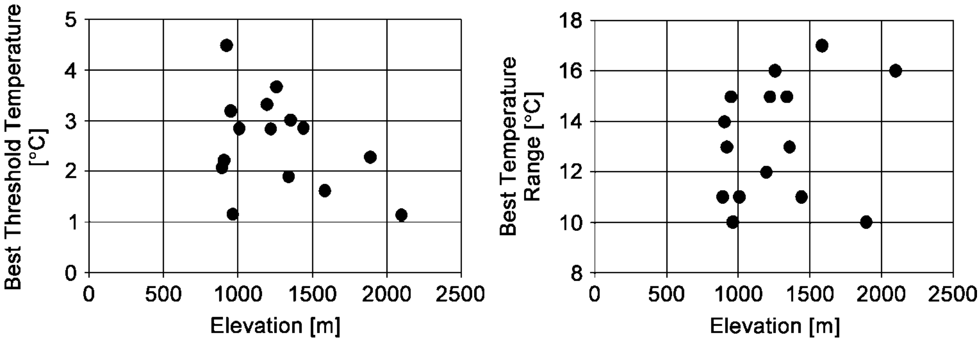

Figure 10. Correlation graphs between best threshold temperature and best temperature range against elevation of the climate stations

Table III. Percentage over- or under-estimation of mean annual snowfall for different estimation methods, based on the same mean annual values for all stations (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Quick and Pipes	Proposed method
Strathmore	2309	−6·9	**−6·1**	−8·2	−10·7
Foremost	2240	**1·2**	4·4	1·9	−2·4
Gleichen	2247	3·6	4·8	2·7	**−0·2**
Claresholm Waterworks	2227	8·4	9·5	8·2	**5·4**
Lethbridge CDA	2265	24·6	26·2	24·9	**22·0**
Fort Macleod	2243	12·2	13·3	11·7	**9·3**
High River	2255	7·1	9·7	6·7	**5·3**
Cardston	2211	15·2	16·0	14·0	**11·1**
Coleman	2381	−1·8	7·6	**−1·7**	−2·9
Pekisko	2427	9·2	11·6	9·4	**6·1**
Carway	2219	7·0	9·1	7·9	**6·7**
Beaver Mines	2366	13·7	17·3	15·0	**13·2**
Fording River Comino	1184	−5·1	**−3·3**	−4·6	−4·6
Fording River Clode Creek	1183	−5·9	**−5·3**	−6·2	−6·6
Natal Harmer Ridge	1203	**0·1**	0·3	0·6	0·7
Mean of absolute values	—	8·1	9·6	8·2	7·1
Median of absolute values	—	7·0	9·1	7·9	6·1
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0.05$	—	0·173	0·016*	0·041*	—

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Table IV. MAS-weighted coefficient of determination between estimated and observed daily snowfall for different estimation methods, based on the same mean annual values for all stations (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Strathmore	2309	0·627	0·634	0·630	**0·636**
Foremost	2240	0·761	0·753	0·784	**0·802**
Gleichen	2247	0·717	0·711	0·744	**0·767**
Claresholm Waterworks	2227	0·726	0·759	0·763	**0·807**
Lethbridge CDA	2265	0·566	0·602	0·599	**0·640**
Fort Macleod	2243	0·648	0·669	0·682	**0·730**
High River	2255	0·733	0·700	0·732	**0·759**
Cardston	2211	0·646	0·647	0·668	**0·698**
Coleman	2381	0·672	0·650	0·690	**0·707**
Pekisko	2427	0·665	0·706	0·708	**0·753**
Carway	2219	0·699	0·729	0·745	**0·773**
Beaver Mines	2366	0·624	0·637	0·646	**0·676**
Fording River Comino	1184	0·717	0·773	0·752	**0·780**
Fording River Clode Creek	1183	0·774	0·778	0·781	**0·789**
Natal Harmer Ridge	1203	0·922	**0·937**	0·932	0·934
Mean	—	0·700	0·712	0·724	**0·750**
Median	—	0·699	0·706	0·732	**0·759**
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·001*	0·001*	0·001*	—

Table V. Percentage over- or under-estimation of mean annual snowfall for different estimation methods, based on individually determined T_T and T_R values for each station (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Quick and Pipes	Proposed method
Strathmore	2309	−0·9	2·3	−8·2	**0·0**
Foremost	2240	1·6	3·7	1·9	**−0·2**
Gleichen	2247	1·3	3·0	2·7	**0·1**
Claresholm Waterworks	2227	1·7	5·0	8·2	**0·8**
Lethbridge CDA	2265	1·1	7·8	24·9	**0·3**
Fort Macleod	2243	**−0·2**	4·3	11·7	**0·2**
High River	2255	0·4	5·3	6·7	**0·1**
Cardston	2211	1·5	5·2	14·0	**0·2**
Coleman	2381	0·6	3·8	−1·7	**0·0**
Pekisko	2427	0·7	5·0	9·4	**0·0**
Carway	2219	0·4	3·5	7·9	**0·1**
Beaver Mines	2366	**0·1**	4·3	15·0	−0·2
Fording River Comino	1184	−0·2	1·7	−4·6	**0·0**
Fording River Clode Creek	1183	1·2	0·9	−6·2	**0·2**
Natal Harmer Ridge	1203	−0·8	**0·0**	0·6	−0·3
Mean of absolute values	—	0·9	3·7	8·2	**0·2**
Median of absolute values	—	0·8	3·8	7·9	**0·2**
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·001*	0·001*	0·001*	—

method that it is compared with. Significant differences are listed with an asterisk in the tables.

Model intercomparison based on the same mean annual values for all stations

In this intercomparison study it was assumed that no detailed information was available for individual climate stations, and the average threshold temperature and temperature range values from Table II were used as default values for all 15 stations. The default values used are a T_T value of 2·6 °C and T_R value of 13·3 °C. Results are listed in Tables III and IV. It is evident from the intercomparison results that, on average, all methods result in quite a wide range of estimation success of mean annual snowfall. Mean annual snowfall is generally over-estimated (Table III), however, some stations are under-estimated by between 6·1 and 10·7%, while other stations are over-estimated by between 22·0 and 26·2%. Two stations consistently had relatively poor estimations, regardless of the method used: Stations 2309 (Strathmore) and 2265 (Lethbridge) had δr^2 values of 0·64 or less. These values are based on both r^2 values between 0·67 and 0·78, but are lowered further by significant under- or over-estimation of mean annual snowfall, particularly

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Table VI. MAS-weighted coefficient of determination between estimated and observed daily snowfall for different estimation methods, based on individually determined T_T and T_R values for each station (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Strathmore	2309	0·672	0·679	0·630	**0·692**
Foremost	2240	0·758	0·770	0·784	**0·821**
Gleichen	2247	0·690	0·727	0·744	**0·766**
Claresholm Waterworks	2227	0·784	0·786	0·763	**0·840**
Lethbridge CDA	2265	0·676	0·668	0·599	**0·742**
Fort Macleod	2243	0·745	0·723	0·682	**0·792**
High River	2255	0·686	0·708	0·732	**0·780**
Cardston	2211	0·675	0·657	0·668	**0·747**
Coleman	2381	0·672	0·684	0·690	**0·718**
Pekisko	2427	0·741	0·744	0·708	**0·792**
Carway	2219	0·728	0·744	0·745	**0·803**
Beaver Mines	2366	0·708	0·691	0·646	**0·752**
Fording River Comino	1184	0·724	0·788	0·752	**0·808**
Fording River Clode Creek	1183	0·730	0·825	0·781	**0·828**
Natal Harmer Ridge	1203	0·913	**0·939**	0·932	0·934
Mean of absolute values	—	0·727	0·742	0·724	**0·788**
Median of absolute values	—	0·724	0·727	0·732	**0·792**
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·001*	0·001*	0·001*	—

Table VII. Percent over- or under-estimation of mean annual snowfall for different estimation methods, based on monthly observed T_T and T_R values (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Quick and Pipes	Proposed method
Strathmore	2309	−1·7	**0·4**	−8·2	−3·2
Foremost	2240	3·5	3·7	1·9	**0·7**
Gleichen	2247	2·9	6·6	2·7	**0·5**
Claresholm Waterworks	2227	3·9	7·5	8·2	**2·9**
Lethbridge CDA	2265	12·0	17·0	24·9	**10·4**
Fort Macleod	2243	**2·9**	8·2	11·7	3·3
High River	2255	**2·4**	7·5	6·7	3·1
Cardston	2211	6·6	10·1	14·0	**5·6**
Coleman	2381	**0·9**	4·7	−1·7	1·3
Pekisko	2427	2·9	9·0	9·4	**2·7**
Carway	2219	4·1	6·7	7·9	**3·9**
Beaver Mines	2366	**7·8**	11·0	15·0	**7·8**
Fording River Comino	1184	−2·1	**−0·3**	−4·6	−2·3
Fording River Clode Creek	1183	**−1·4**	−2·8	−6·2	−2·8
Natal Harmer Ridge	1203	1·9	1·5	**0·6**	1·4
Mean of absolute values	—	3·8	6·5	8·2	**3·5**
Median of absolute values	—	**2·9**	6·7	7·9	**2·9**
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·910	0·004*	0·001*	—

at the Lethbridge station. The newly proposed method consistently resulted in both overall best estimations of mean annual snowfall and highest coefficients of determination. The second best was, on average, the Pipes and Quick method, followed by the Leavesley *et al.* method, and lastly the static threshold method. Four stations exhibited mean annual snowfall estimation errors of over 10%, which shows the need for individually selected threshold temperatures.

In all cases, the proposed method resulted in significantly higher r^2 values than the other three methods, with the exception of Station 1203, where the Leavesley *et al.* method provided the same high r^2 value of 0·94. In 14 out of 15 cases, the proposed method resulted in the highest δr^2 values, with overall significantly better estimation values (Table IV).

Model intercomparison based on observed best annual values for each station

Due to careful selection of representative threshold temperatures and temperature ranges determined during the sensitivity analyses, the results of the intercomparison analyses are much improved for all methods investigated (Tables V and VI) compared with results listed in

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Table VIII. MAS-weighted coefficient of determination between estimated and observed daily snowfall for different estimation methods, based on monthly observed T_T and T_R values (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Strathmore	2309	0·687	0·729	0·630	**0·731**
Foremost	2240	0·752	0·795	0·784	**0·834**
Gleichen	2247	0·715	0·719	0·744	**0·791**
Claresholm Waterworks	2227	0·804	0·786	0·763	**0·846**
Lethbridge CDA	2265	0·702	0·674	0·599	**0·746**
Fort Macleod	2243	0·833	0·772	0·682	**0·848**
High River	2255	0·769	0·738	0·732	**0·813**
Cardston	2211	0·739	0·715	0·668	**0·775**
Coleman	2381	0·673	0·684	0·690	**0·718**
Pekisko	2427	0·772	0·750	0·708	**0·823**
Carway	2219	0·805	0·791	0·745	**0·816**
Beaver Mines	2366	0·690	0·696	0·646	**0·736**
Fording River Comino	1184	0·754	**0·815**	0·752	0·795
Fording River Clode Creek	1183	0·751	**0·800**	0·781	0·787
Natal Harmer Ridge	1203	0·910	0·929	0·932	**0·931**
Mean	—	0·757	0·760	0·724	**0·799**
Median	—	0·752	0·750	0·732	**0·795**
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·001*	0·003*	0·001*	—

Table IX. Percentage over- or under-estimation of mean annual snowfall for different estimation methods, based on adjusted monthly sin curve values for T_T and T_R (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Quick and Pipes	Proposed method
Strathmore	2309	0·7	6·8	−8·2	**0·5**
Foremost	2240	2·6	11·1	1·9	**1·4**
Gleichen	2247	2·8	11·4	2·7	**1·6**
Claresholm Waterworks	2227	**0·3**	10·7	8·2	0·6
Lethbridge CDA	2265	**3·6**	22·9	24·9	**3·6**
Fort Macleod	2243	0·3	12·7	11·7	**0·2**
High River	2255	**4·1**	16·7	6·7	4·3
Cardston	2211	**4·1**	17·0	14·0	4·4
Coleman	2381	−2·5	10·4	**−1·7**	−4·1
Pekisko	2427	**5·5**	22·9	9·4	5·7
Carway	2219	5·9	15·3	7·9	**5·7**
Beaver Mines	2366	3·7	19·4	15·0	**3·3**
Fording River Comino	1184	**0·4**	5·1	−4·6	0·6
Fording River Clode Creek	1183	1·0	4·0	−6·2	**0·7**
Natal Harmer Ridge	1203	4·0	6·2	0·6	**3·9**
Mean of absolute values	—	2·8	12·8	8·2	**2·7**
Median of absolute values	—	4·8	6·7	4·8	**4·8**
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·650	0·001*	0·005*	—

Tables III and IV. The mean annual snowfall was best estimated using the proposed curvilinear method, with a mean estimation error of 0·2%, ranging for individual stations between 0·0 and 0·8%. The static threshold method also provided excellent mean annual snowfall estimation results, with a mean estimation error of 0·9%, ranging for individual stations between 1·7 and 0·2%. As the Quick and Pipes method is independent of the threshold temperature, it also has the largest estimation errors of mean annual snowfall, with a mean estimation error of 8·2%, ranging from 0·6% at the alpine station to 24·9% at the prairie station in Lethbridge. These results clearly show that the method was designed for alpine regions in British Columbia, usually performs best in locations with higher elevations and is not applicable for prairie stations. The Leavesley *et al.* method uses, in addition to the threshold temperature, daily minimum and maximum temperatures, which can result in some deviations in daily snowfall estimations. The Leavesley *et al.* method generally provided the best results for stations with high elevations and high proportions of snow fall. This method resulted in a mean estimation of annual snowfall of 3·7%, ranging from 0·9% at the alpine station 1203 to 7·8% at the prairie station at Lethbridge. Overall, the proposed

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method provided significantly better results than the other three methods.

All methods resulted in mean and median r^2 values above 0·72. The static threshold method has a mean r^2 value of 0·733, ranging from 0·92 to 0·677. The Pipes and Quick method is the best method at two alpine stations and one prairie station, with r^2 values of 0·833, 0·939 and 0·695 respectively, and has a mean r^2 value of 0·769. The Leavesley *et al*. method is the best method at four stations (both foothills and prairie stations) and has a mean r^2 values of 0·781. The proposed method resulted in significantly higher r^2 values when compared to the other three methods, with a mean r^2 value of 0·789, and being the best method in 10 out of 15 stations, and always being very close to best r^2 values at the other stations.

The δr^2 values are highest for 14 out of 15 station when using the proposed method, with an overall mean value of 0·788 (Table VI). The second best method is the Pipes and Quick method with a mean δr^2 value of 0·742, followed by the Leavesley *et al*. method with a mean δr^2 value of 0·724, and the static threshold method with a mean δr^2 value of 0·727. On average, the proposed method can explain the snow proportion of daily precipitation to almost 80% from mean daily air temperature. Based on the MAS-weighted coefficient of determination, the proposed method provides significantly better results than the other three methods.

Seasonal variations of the threshold temperature and temperature range

Due to strong seasonal changes in the regional climate, it can be expected that the threshold temperature and temperature ranges also change during the seasons. Lauscher (1982, in Braun 1985) and Rohrer (1989) have shown seasonal differences in threshold temperatures. When one graphs the proportion of precipitation that falls as snow against the mean daily temperature for a single month (Figure 11), there is considerable scatter, compared with snow proportions based on all available values (Figure 6). Figure 11 presents temperature versus snow proportion curves for four representative months for a high elevation station (Station 1203) and one station in the prairies (Station 2365). Investigation of all monthly precipitation records revealed that most climate stations have exclusively snowfall during some winter months and exclusively rainfall during some summer months (Figure 11). The selected threshold temperatures and temperature ranges of 0 °C for January and July for Station 1203 and July for Station 2265 are arbitrary and inconsequential, as all observed precipitation is in the form of either snow or rain.

The s-shaped curve describing the relationship between mean daily temperature and snow proportion is often not clearly defined, as is the case for Station 1203 (April) and 2265 (January, April and October). Consequently, the threshold temperatures or temperature ranges could not be derived for all months and for all stations. Figure 12 presents all identifiable threshold temperatures in an attempt to generate an observable pattern, universal for the study area. In order to enable the visual presentation of all estimated threshold temperatures and avoid overlapping points, the threshold temperatures for stations with the same temperature were slightly displaced (either increased or decreased). A strong seasonal oscillation is evident for the threshold temperature, with a maximum in winter and a minimum in summer.

A sine curve fits the seasonal oscillation, based on mean monthly data (displayed as a dashed line in Figure 12), very well ($r^2 = 0{\cdot}958$), with the exception of the month of January. While analyses of individual climate station records show a wide range of threshold temperatures, a generally relevant sine curve can be established. In order to adjust the sine curve to better represent individual stations, it can be scaled according to the mean annual threshold temperatures listed in Table II:

$$T_{MTS} = T_T + (T_T \times \sin((M_i + 2)/1{\cdot}91)) \qquad (6)$$

with T_{MTS} = monthly threshold temperature based on the sine curve, T_T = observed mean annual threshold temperature (Table II), and M_i = month from 1 to 12.

Similar to the threshold temperature, an attempt is made to represent the seasonal variation of the temperature ranges using a universal equation. Figure 13 shows the mean monthly temperature ranges for all identifiable temperature range estimations. To facilitate a generic estimation of monthly temperature ranges, the monthly temperature ranges are expressed as proportions of the temperature range values listed in Table II. It is interesting to note that no month reaches the full temperature range derived on the full data sets and presented in Table II. In order to estimate the mean temperature range proportions based on this model, the values shown in Figure 13 need to be multiplied by the best temperature ranges values from Table II. It appears that there is a clear distinction between temperature ranges based on annual data (Table II) and those based on monthly data. Temperature ranges for the separation of snow from rain are much less distinctive during winter and summer, to the point where they become meaningless (Figure 11). It appears that the temperature ranges follow a two-cycle curve during a year, with two peaks during spring and fall, and two troughs during summer and winter. An equation was derived to represent these annual oscillations:

$$T_{MRS} = T_R \times (0{\cdot}55 + (\sin(M_i + 4)) \times 0{\cdot}6 \qquad (7)$$

with T_{MRS} = monthly temperature range based on sine curve, T_R = annual temperature range (Table II), and M_i = month from 1 to 12.

To avoid negative values, all values below zero are converted to zeroes. The derived sine curve matches the mean temperature range proportions very well ($r^2 = 0{\cdot}963$). However, the month of January would be slightly under-estimated using this method.

In order to test if monthly temperature threshold and temperature range values improve the division of the precipitation records into snow and rain, two types of monthly estimations were compared with observed data.

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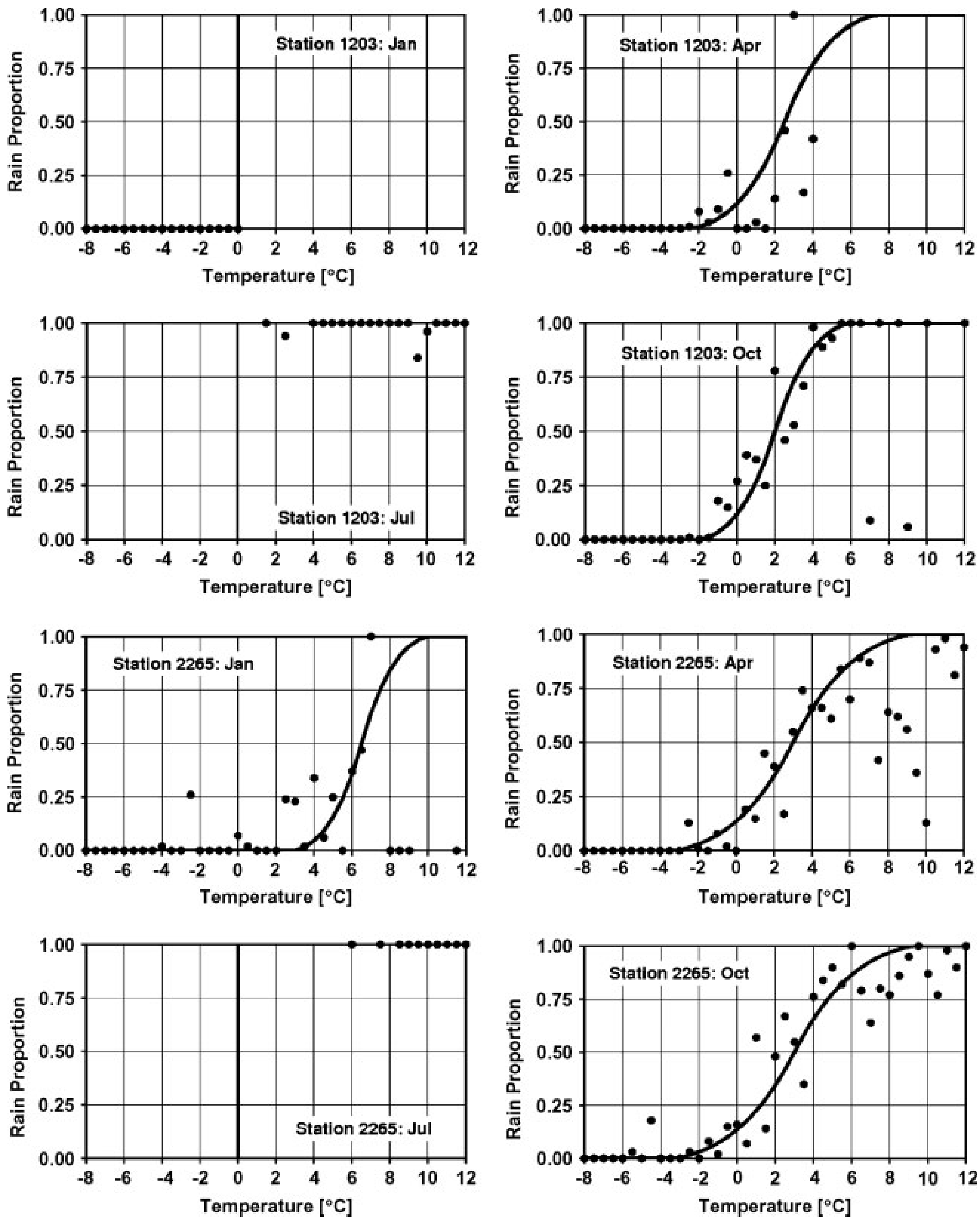

Figure 11. The threshold temperature and temperature ranges undergo strong seasonal changes, as is shown for Stations 1203 and 2265

One estimation was based on individual values derived from monthly graphs, and one was based on the general mean sine oscillation values, adjusted according to Equations (6) and (7). In the former case, where monthly values could not be derived due to the occurrence of one precipitation type, a threshold temperature value of 10 °C was used for winter months to force all precipitation to be snow, and a threshold temperature value of 0 °C was used for the summer months in order to force all precipitation to be rain.

Model intercomparison based on observed monthly values for each station

Using T_T and T_R values based on monthly observations for each climate station, the proposed method and static threshold methods resulted in the best mean annual snowfall estimations (Table VII), with mean errors of 3·5% and 3·8%, respectively. The Leavesley *et al.* method produced a mean error of estimating mean annual snowfall of 6·5%, while the Pipes and Quick method resulted in a mean error of 8·2%. Coefficients of determination were higher than with the annual T_T and T_R values. The lowest r^2 values were produced with the static threshold method, with a mean r^2 value of 0·786, ranging from 0·679 to 0·928. As the Pipes and Quick method is independent of the T_T and T_R values, it resulted in the same r^2 value of 0·781 as in the previous intercomparison analyses. The Leavesley *et al.* method produced mean r^2 values of 0·807, ranging from 0·716 to 0·944. The proposed method resulted in significantly

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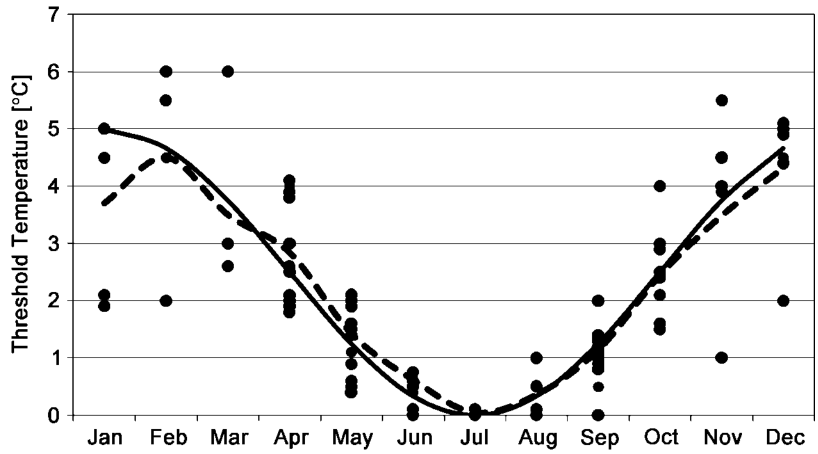

Figure 12. Observed monthly threshold temperatures values for all 15 climate stations, with calculated mean values (dashed line) and fitted sine curve (black line)

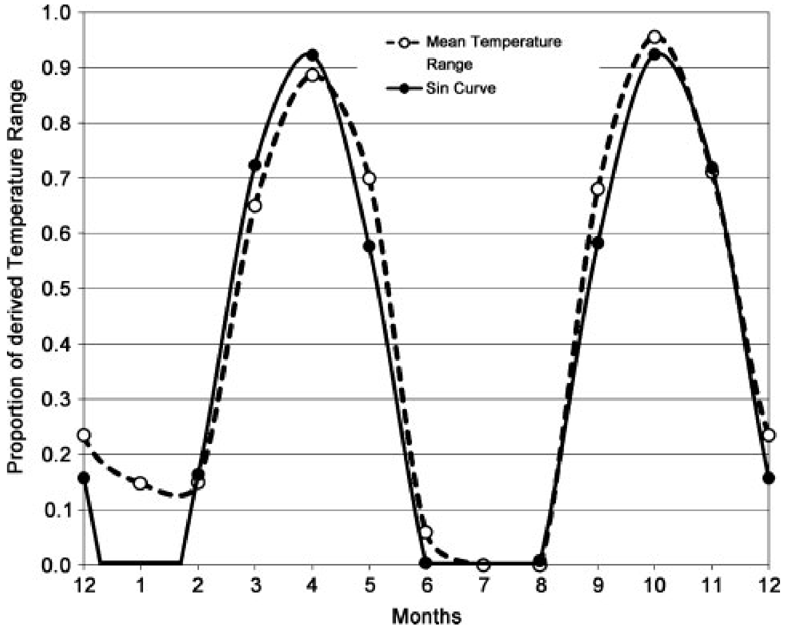

Figure 13. Sine curve representing the mean monthly observable temperature ranges. Values below zero are forced to be zero

higher r^2 values, ranging from 0·728 to 0·944, with a mean of 0·828.

For 13 out of 15 climate stations tested, the proposed method produced the highest δr^2 values, with the other two being produced by the Leavesley *et al.* method (Table VIII). The Pipes and Quick method, not being able to take advantage of monthly changing values, produced overall the lowest mean δr^2 value of 0·724. The static threshold method and the Leavesley *et al.* method resulted in similar mean δr^2 values of 0·757 and 0·760. Again, the proposed method resulted in significantly higher mean δr^2 value of 0·799.

Model intercomparison based on the mean sine oscillation values adjusted for each station

Using T_T and T_R values based on the mean sine oscillation values adjusted for each climate station, the proposed method and the static threshold methods again resulted in the best mean annual snowfall estimations (Table IX), with mean errors of 2·2% and 2·4% respectively, both having a similar range from 0·2% (0·3%) to 5·7% (5·9%). The Leavesley *et al.* method produced a mean error of estimating mean annual snowfall of 12·8%, substantially higher than when it was based on observed monthly values. The Pipes and Quick method resulted in a same mean error of 8·2%, being independent of the choice of T_T and T_R values.

Coefficients of determination were slightly lower than with the approach of using observed monthly T_T and T_R values. The lowest r^2 values were produced with the Leavesley *et al.* method, resulting in a mean r^2 value of 0·758, ranging from 0·661 to 0·933. The static threshold method produced a mean r^2 value of 0·773, ranging from 0·676 to 0·921. As the Pipes and Quick method is independent of the T_T and T_R values, it resulted again in the same r^2 value of 0·781, as in the previous intercomparison analyses. Consistent with previous intercomparisons, the proposed

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Table X. MAS-weighted coefficient of determination between estimated and observed daily snowfall for different estimation methods, based on adjusted monthly sine curve values for T_T and T_R (best values are in bold)

Station	Station ID	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Strathmore	2309	0·682	0·653	0·630	**0·728**
Foremost	2240	0·762	0·709	0·784	**0·829**
Gleichen	2247	0·705	0·674	0·744	**0·774**
Claresholm Waterworks	2227	0·830	0·727	0·763	**0·870**
Lethbridge CDA	2265	0·737	0·604	0·599	**0·784**
Fort Macleod	2243	0·814	0·683	0·682	**0·863**
High River	2255	0·755	0·649	0·732	**0·812**
Cardston	2211	0·727	0·595	0·668	**0·779**
Coleman	2381	0·659	0·599	**0·690**	0·689
Pekisko	2427	0·744	0·602	0·708	**0·790**
Carway	2219	0·786	0·688	0·745	**0·812**
Beaver Mines	2366	0·724	0·597	0·646	**0·777**
Fording River Comino	1184	0·723	0·717	0·752	**0·780**
Fording River Clode Creek	1183	0·743	0·738	0·781	**0·809**
Natal Harmer Ridge	1203	0·885	0·879	**0·932**	0·900
Mean	—	0·752	0·674	0·724	0·800
Median	—	0·743	0·674	0·732	0·790
2-tailed Wilcoxon Signed Ranks significance value compared to proposed method, $\alpha = 0{\cdot}05$	—	0·001*	0·001*	0·002*	—

method resulted in significantly higher r^2 values, ranging from 0·718 to 0·935, with a mean r^2 value of 0·821.

For 13 out of 15 climate stations tested, the proposed method produced the highest δr^2 values, with the other two being produced by the Quick and Pipes method (Table X). The Leavesley *et al.* method resulted in the lowest mean δr^2 value of 0·674, mainly because of the relatively high error in estimating mean annual snowfall when using T_T and T_R values based on the monthly sin oscillation. The Pipes and Quick method, not being able to take advantage of monthly changing values, produced overall the lowest mean δr^2 value of 0·724. The static threshold method resulted in a mean δr^2 value of 0·752. Again, the proposed method resulted in a significantly higher mean δr^2 value of 0·800.

CONCLUSIONS AND RECOMMENDATIONS

Similar to observations made in the European Alps (L'Hote *et al.*, 2005), Switzerland (Rohrer, 1989), the South American Andes (L'Hote *et al.*, 2005), the USA (Auer, 1974; Fassnacht *et al.*, 2001) Finland (Vehviläinen, 1992) and Norway (Forland, 2003), the investigation in south-western Alberta, Canada, of the separation of precipitation into rain and snow as a function of air temperature resulted in an s-shaped curve. The shape of the curve is quite consistent for the 15 climate station investigated. The shape of the curve was mathematically described, using two observable variables, the threshold temperature T_T, where 50% of the precipitation falls as snow, and the temperature range T_R, within which the transition from rain to snow occurs. Consequently, one can distinguish for any precipitation day between 100% snow (T_T lower than the beginning of the s-curve), 100% rain (T_T above the end of the s-curve), and mixed precipitation, where a T_T dependent proportion is snow, and the rest is rain. A sensitivity analysis using a total of 963 years of daily precipitation observations, revealed that the sensitivity of the threshold temperature on mean annual snowfall estimations was quite similar for all climate stations. The change per degree T_T resulted in an average change in mean annual snowfall estimation of 8·7%, and a modest change in mean r^2 of 0·029. It was found that a change in T_R has little effect on the estimation of mean annual snowfall, with average changes of 0·11% per degree increase in temperature range. However, T_R does affect the r^2 value. When one compares the coefficient of determination of estimates with a T_R of zero with estimates based on the best T_R, the average improvement is an increase in the r^2 value of 0·064.

A series of model intercomparison analyses was carried out, investigating the success of estimating snowfall from precipitation records and ground air temperature using four different methods, including the newly proposed method, under four different input data conditions. Mean results of the three objective functions used are summarized in Tables XI, XII and XIII. Consistently, the newly proposed method resulted in the best estimation of mean annual snowfall (Table XI), although the static threshold method is a very close contender. Also consistently, the proposed method produces the highest r^2 values (Table XII). Consequently, the proposed method also results in the highest MAS-weighted coefficients of determination (Table XIII). It can be concluded that, for the climate stations tested, the proposed method results in significantly better annual and daily snowfall estimations than the other three methods tested, under all four input data conditions.

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Table XI. Summary of the percent error of mean annual snowfall estimations for all methods tested

Estimation method	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Mean annual values for all stations	8·1	9·6	8·2	**7·1**
Observed annual values for each station	0·9	3·7	8·2	**0·2**
Observed monthly values for each station	3·8	6·5	8·2	**3·5**
Sine curve based monthly values for each station	2·8	12·8	8·2	**2·7**

Table XII. Summary of the mean coefficients of determination between estimated and observed daily snowfall for all methods tested

Estimation method	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Mean annual values for all stations	0·754	0·778	0·781	**0·802**
Observed annual values for each station	0·733	0·769	0·781	**0·789**
Observed monthly values for each station	0·786	0·807	0·781	**0·828**
Sine curve based monthly values for each station	0·773	0·758	0·781	**0·821**

Table XIII. Summary of mean MAS-weighted coefficient of determination for all methods tested

Estimation method	Static threshold	Leavesley *et al.*	Pipes and Quick	Proposed method
Mean annual values for all stations	0·700	0·712	0·724	**0·750**
Observed annual values for each station	0·727	0·742	0·724	**0·788**
Observed monthly values for each station	0·757	0·760	0·724	**0·799**
Sine curve based monthly values for each station	0·752	0·674	0·724	**0·800**

The question arises, which method should be applied under different scenarios of data availability. The following recommendations can be made based on the analyses carried out in this investigation:

A. If no climate data with observed rain and snowfall exist, then the mean annual T_T and T_R values listed in Table II may serve as initial default values. Equations (6) and (7) for the estimation of monthly T_T and T_R values based on a sine oscillation should be used, and the monthly T_T and T_R estimates should then be applied in Equation (2). However, empirical observation with regard to T_T close to the particular region should be given preference.

B. If one or more climate stations in a particular region do have observation of both rain and snow, then the following procedure should be applied:

a. determine the shape of the curve describing the snow and rain proportions versus daily mean ground air temperature (see Figure 6),

b. determine T_T and T_R visually or mathematically from the curves,

i. if the record of both precipitation and temperature observation is short (i.e. less than 10 years), then derive a curve only for all observed values, determine annual T_T and T_R values, and apply them in Equations (6) and (7) for the estimation of monthly T_T and T_R values based on a the sine oscillation equations; then apply the resulting monthly T_T and T_R estimates in Equation (2);

ii. if the record of both precipitation and temperature observation is long (i.e. 30 years or more), then derive monthly snow proportion curves, determine monthly T_T and T_R values (see Figure 11), and apply the derived monthly T_T and T_R values directly in Equation (2).

If a user has a preference for using another estimation method, or where a method is proven to work in a particular region, such as Pipes and Quick in the alpine areas of British Columbia, Canada, monthly varying threshold temperatures or adjusted linear transition equations should be used, as they are likely to result in a better estimation of snowfall (Tables XI, XII and XIII).

The proposed method should be tested in other climate regions to gain confidence in its universal validity.

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REFERENCES

Auer AH. 1974. The rain versus snow threshold temperatures. *Weatherwise* **27**: 67.

Bergström S. 1995. The HBV Model. In *Computer Models of Watershed Hydrology*, Singh VP (ed). Water Resources Publications: Colorado; 443–476.

Braun LN. 1985. Simulation of snowmelt-runoff in lowland and lower alpine regions of Switzerland. Dissert. *Zürcher Geographische Schriften, Heft 21*. (ETH) Zürich.

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Byrne JM, Berg A, Townshend I. 1999. Linking observed and general circulation model upper air circulation patterns to current and future snow runoff for the Rocky Mountains. *Water Resources Research* **35**: 3793–3802.

Devine KA, Mekis É. 2008. Field Accuracy of Canadian Rain Measurements. *Atmosphere-Ocean* **46**: 213–227.

Dingman SL. 2002. *Physical Hydrology*. Prentice-Hall: New Jersey; 646.

Dunn SM, Colohan RJE. 1999. Developing the snow component of a distributed hydrological model: a step-wise approach based on multi-objective analysis. *Journal of Hydrology* **223**: 1–16.

Fassnacht SR, Kouwen N, Soulis ED. 2001. Surface temperature adjustments to improve weather radar representations of multi-temporal winter precipitation accumulations. *Journal of Hydrology* **253**: 148–168.

Fassnacht SR, Soulis ED. 2002. Implications during transitional periods of improvements to the snow processes in the land surface scheme—Hydrological Model WATCLASS. *Atmosphere-Ocean* **40**: 389–403.

Goodison BE. 1981. Compatibility of Canadian snowfall and snow cover data. *Water Resources Research* **17**: 893–900.

Goodison BE, Metcalfe JR. 1981. An experiment to measure fresh snowfall water equivalent at Canadian climate stations. In *Proceedings of 38th Eastern Snow Conference*, Syracuse, NY, USA, 4–5 June, 1981; 110–112.

Goodison BE, Metcalfe JR. 1992. The WMO solid precipitation measurement intercomparison: Canadian assessment. In *WMO Technical Conference on Instruments and Method of Observation*, WMO/TD No.462. WMO: Geneva; 221–225.

Gray DM, Prowse TD. 1993. Snow and floating ice. In *Handbook of Hydrology,* Maidment DR (ed). McGraw-Hill: New York; 7·1–7·58.

Kite GW. 1995. The SLURP Model. In *Computer Models of Watershed Hydrology*, Singh VP (ed). Water Resources Publications: Colorado; 521–562.

Lapp S, Byrne J, Kienzle SW, Townshend I. 2002. Linking GCM synoptics and precipitation for western North America. *International Journal of Climatology* **22**: 1807–1817.

Lapp S, Byrne J, Townshend I, Kienzle SW. 2005. Climate warming impacts on snowpack accumulation in an alpine watershed: A GIS based modelling approach. *International Journal of Climatology* **25**: 521–536.

Leavesley GH, Lichty RW, Troutman BM, Saindon LG. 1983. Precipitation-Runoff Modeling System: User's Manual. Water Resources Investigations Report 83–4238, US Geological Survey, Denver, Colorado.

L'Hôte Y, Chevallier P, Coudrain A, Lejeune Y, Etchevers P. 2005. Relationship between precipitation phase and air temperature: comparison between the Bolivian Andes and the Swiss Alps. *Hydrological Sciences Journal* **50**: 989–997.

Loth B, Graf H-F, Oberhuber JM. 1993. Snow cover model for global climate simulations. *Journal of Geophysical Research* **98**: 10451–10464.

Metcalfe JR, Routledge B, Devine K. 1996. Rainfall measurement in Canada: Changing observational methods and archive adjustment procedures. *Journal of Climate* **10**: 92–101.

Motoyama H. 1990. Simulation of seasonal snowcover based on air temperature and precipitation. *Journal of Applied Meteorology* **29**: 1104–1110.

Pietroniro A, Fortin V, Kouwen N, Neal C, Turcotte R, Davison B, Verseghy D, Soulis ED, Caldwell R, Evora N, Pellerin P. 2007. Development of the MESH modelling system for hydrological ensemble forecasting of the Laurentian Great Lakes at the regional scale. *Hydrology and Earth System Science* **11**: 1279–1294.

Pigeon K, Jiskoot H. in press. Meteorological controls on snowpack formation and dynamics in the southern Canadian Rocky Mountains. *Arctic, Antarctic and Alpine Research*.

Pipes A, Quick MC. 1977. *UBC Watershed Model Users Guide*. Department of Civil Engineering, University of British Columbia: Vancouver, British Columbia, Canada.

Rachner M, Matthäus H. 1984. Schneehydrologische Untersuchungsergebnisse in der DDR und deren Anwendung für wasserwirtschaftliche Zwecke (in German). *DVWK-Mitteilungen* **7**: 235–255.

Rachner M, Matthäus H, Schneider G 1997. Echtzeitvorhersage der Schneedeckenentwicklung und der Wasserabgabe aus der Schneedecke. Erste Ergebnisse aus dem Projekt SNOW-D (in German). *Deutsche Gewässerkundliche Mitteilungen* **41**: 98–106.

Rango A 1995. The Snowmelt Runoff Model (SRM). In *Computer Models of Watershed Hydrology*, Singh VP (ed). Water Resources Publications: Colorado; 477–520.

Rohrer MD. 1989. Determination of the transition air temperature from snow to rain and intensity of precipitation. In *IAHS/WMO/ETH International Workshop of Precipitation Measurement*, Sevruk B (ed). St. Moritz, Switzerland; 475–482.

Rolland C. 2003. Spatial and seasonal variations of air temperature lapse rates in alpine regions. *Journal of Climate* **16**: 1032–1046.

Rood SB, Samuelson GM, Weber JK, Wywrot KA. 2005. Twentiethcentury decline in streamflows from the hydrographic apex of North America. *Journal of Hydrology* **306**: 215–233.

Sevruk B. 1984. Assessment of snowfall proportion in monthly precipitation in Switzerland. *DVWK-Mitteilungen* **7**: 601–603.

USCE. 1956. Snow hydrology, Summary report of the snow investigations. North Pacific Division, US Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Vehviläinen B. 1992. Snow cover models in operational watershed forecasting. Publications of the Water and Environment Research Institute, National Board of Waters and the Environment, Finland, Helsinki, **11**: 112.

Yang Z-L, Dickinson RE, Robock A, Vinnikov KY. 1997. Validation of the snow submodel of the Biosphere–Atmosphere Transfer Scheme with Russian snow cover and meteorological observational data. *Journal of Climate* **10**: 353–373.

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