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Inconsistency in precipitation measurements across the Alaska–Yukon border

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Abstract. This study quantifies the inconsistency in gauge precipitation observations across the border of Alaska and Yukon. It analyses the precipitation measurements by the national standard gauges (National Weather Service (NWS) 8 in. gauge and Nipher gauge) and the bias-corrected data to account for wind effect on the gauge catch, wetting loss and trace events. The bias corrections show a significant amount of errors in the gauge records due to the windy and cold environment in the northern areas of Alaska and Yukon. Monthly corrections increase solid precipitation by 136 % in January and 20 % for July at the Barter Island in Alaska, and about 31 % for January and 4 % for July at the Yukon stations. Regression analyses of the monthly precipitation data show a stronger correlation for the warm months (mainly rainfall) than for cold month (mainly snowfall) between the station pairs, and small changes in the precipitation relationship due to the bias corrections. Double mass curves also indicate changes in the cumulative precipitation over the study periods. This change leads to a smaller and inverted precipitation gradient across the border, representing a significant modification in the precipitation pattern over the northern region. Overall, this study discovers significant inconsistency in the precipitation measurements across the USA–Canada border. This discontinuity is greater for snowfall than for rainfall, as gauge snowfall observations have large errors in windy and cold conditions. This result will certainly impact regional, particularly cross-border, climate and hydrology investigations.

1 Introduction

It is known that discontinuities in precipitation measurements may exist across the national boundaries because of the different instruments and observation methods used (Nitu and Wong, 2010; Sanderson, 1975; Sevruk and Klemm, 1989; Yang et al., 2001). For instance, the National Weather Service (NWS) 8 in. gauge is used for precipitation measurements in the United States (USA), and the Nipher snow gauge has been used in Canada for decades. Different instruments have also been used in various observational networks within the same country. In the synoptic network, the Type-B rain gauge and Nipher gauge are the standard manual instruments for rain and snow observations in Canada (Mekis and Vincent, 2011; Metcalfe and Goodison, 1993), and recently the Geonor automatic gauges have been installed.

Instruments also change over time at most operational networks, resulting in significant breaks in data records. It has been realized that combination of regional precipitation records from different sources may result in inhomogeneous precipitation time series and can lead to incorrect spatial interpretations (Yang et al., 2005). Efforts have been reported to examine the precipitation discontinuity within a country (Groisman and Easterling, 1994; Sanderson, 1975). Leeper et al. (2015) found that the US Cooperative Observer Program (COOP) Network stations reported slightly more precipitation overall (1.5 %), with network differences varying seasonally. The COOP gauges were sensitive to wind biases, particularly over winter when COOP observed (10 %) less precipitation than the US Climate Refer-

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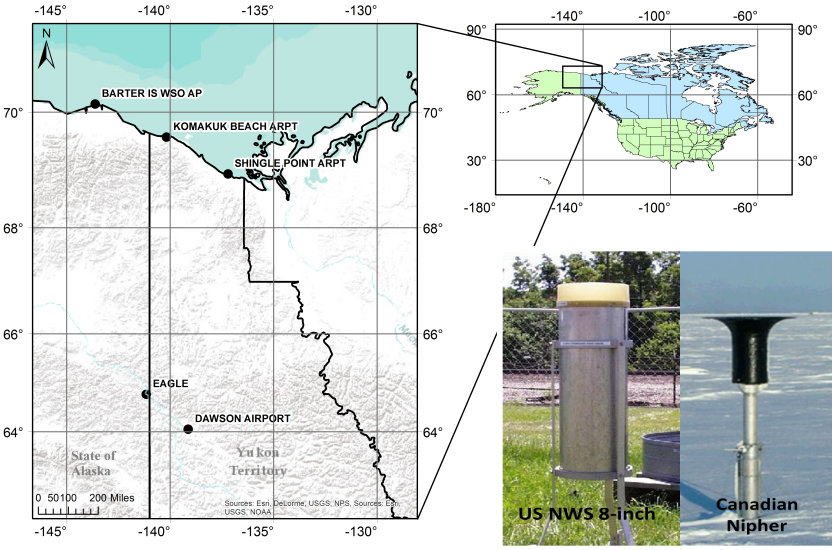

Figure 1. Study areas and locations of selected climate stations, and photos of the national standard gauges, NWS 8 in. gauge (left) and the Nipher snow gauge (right), respectively, for the USA and Canada.

ence Network (USCRN). Conversely, wetting and evaporation losses, which dominate in summer, were sources of bias for USCRN. Mekis and Brown (2010) developed adjustment method to link the Nipher gauge and ruler snowfall measurements over Canada. Yang and Simonenko (2013) compared the measurements among six Russian Tretyakov gauges at the Valdai experimental station and reported differences of less than 5–6 % for the study period. These results are useful to determine the homogeneity of precipitation data collected by a standard gauge within the national and regional networks.

Many studies show that the national standard gauges, including the Canadian Nipher and US 8 in. gauges, undermeasure precipitation, especially for snowfall (Goodison, 1981; Goodison et al., 1998; Yang et al., 1995, 1998a, 1999). Compatibility analysis of precipitation measurements by various national gauges suggests little difference (less than 5 %) for rainfall observations, but a significant discrepancy (up to 110 %) for snowfall measurements (Yang et al., 2001). For instance, the experimental data from Valdai show that the US 8 in. gauge at Valdai systematically measured 30–50 % less snow and mixed precipitation than the Canadian Nipher gauge (Yang et al., 2001). This difference in national gauge catch has introduced a significant discontinuity in precipitation records across the USA–Canada border, particularly in windy and cold regions. Differences in the snow measurements across the USA–Canada border have also been noticed in other studies as problematic for producing gridded products and for developing precipitation input for basin hydrological investigations (Šeparović et al., 2013; Zhao et al., 2010).

Although Yang et al. (2001) compared the relative catch of many national standard gauges, little has been done to address the inconsistency of precipitation records across the national borders. This is an important issue, since most regional precipitation data and products have been compiled and derived from the combination of various data sources, assuming these data and observations were compatible across the borders and among the national observational networks. Simpson et al. (2005) studied temperature and precipitation distributions over the state of Alaska (AK) and west Yukon (YK), and documented precipitation increase from north to south. They also report differences in mean monthly precipitation across the Alaska–Yukon border, i.e. about 5–15 mm in central-east Alaska and 15–40 mm in central-west Yukon. Jones and Fahl (1994) found a weak gradient in annual precipitation across the AK–YK border, including the headwaters of the Yukon River. Other studies also discuss precipitation distribution and changes over the Arctic regions (Legates and Willmott, 1990; Serreze and Hurst, 2000; Yang et al., 2005).

The objective of this work is to examine the inconsistency in precipitation measurements across the border between Alaska and Yukon. We analyse both gauge-measured and bias-corrected monthly precipitation data at several climate stations across the border, and quantify the changes in precipitation amounts and patterns due to the bias corrections. We also calculate the precipitation gradients across the border and discuss precipitation distribution for the warm and cold seasons. The methods and results of this study are useful for cold-region climate and hydrology investigations and applications.

Table 1. Station information and climate summary.

ID WMO	Country	Station name	Location			Data period		Measurement device	Annual means				
			Lat (°)	Lon (°)	Altitude (m)	Start	End	Precipitation gauge	Precipitation (mm)	Missing precipitation data (%)	Min. temp. (°C)	Max. temp. (°C)	Wind speed ($\mathrm{m\,s^{-1}}$)
700860	USA	Barter IS WSO AP	70.13	−143.63	11	1978	1988	US 8 in. unshielded	155	0.3	−27.1	4.6	4.0
719690	CA	Komakuk Beach ARPT	69.58	−140.18	7	1978	1988	Nipher Type-B gauge	191.8	2.9	−27.5	7.4	3.9
719680	CA	Shingle Point ARPT	68.95	−137.21	49	1978	1988	Nipher Type-B gauge	302	6	−26.6	10.6	3.4
701975	USA	Eagle	64.78	−141.16	268	2006	2013	US 8 in. unshielded	247	0.2	−22.7	15.5	0.9
719660	CA	Dawson Airport	64.05	−139.13	369	2006	2013	Nipher Type-B gauge	258	0.6	−25.8	15.9	1

2 Study area, data and methods

The study areas include the northern and central regions of Alaska and Yukon. We choose five climate stations across the Yukon–Alaska border, which use the national standard gauges (NWS 8 in. gauge and the Canadian Nipher gauge) for precipitation observations (Fig. 1). These stations can be classified into two groups. The first group, three stations about 150 km apart, is the northern region along the coast of the Beaufort Sea, with the Barter Island station in Alaska and Komakuk and Shingle Point stations in Yukon. The second group is in the central part of the region: the Eagle station in Alaska and Dawson station in Yukon, about 130 km apart.

The three northern stations selected for this study are located north of the Brooks Range. The approximate distances to the mountain edge are 100 km for the Barter Island station, 90 km for Shingle Point station, and 150 km for the Komakuk station. Both stations in Yukon are along the shoreline, and the station in Alaska is an island site, very close to the coastline. The altitudes of the stations range from 7 to 49 m a.s.l. According to Manson and Solomon (2007), the summer storm tracks are usually from the northwest, coming from the open water in the Beaufort Sea, and are the greatest contributor to annual precipitation. The storms are obstructed by the Brooks Range once moving inland. The weather patterns in the surrounding of the stations might be affected by the mountains, but the stations are not separated by the Brooks Range. Given this setting, it is expected to see little impact of mountain range on the precipitation process and distribution along the relatively flat coastline.

These stations have been operated by the NWS and Environment Canada (EC) since the early 1970s. The observations have been done according to the national standards of the USA and Canada. The detailed information for these stations is given in Table 1, such as the location; period of measurement used for this work; instrument types for precipitation observations; and a climate summary for yearly temperature, precipitation, and wind speed.

Yang et al. (2005) have developed a bias-corrected daily precipitation data set for the northern regions above 45° N. The source data are acquired from the National Centers for Environmental Information (NCEI), i.e. a global daily surface data archive for over 8000 stations around the world (https://www.ncdc.noaa.gov/data-access/quick-links#ghcn). To focus on the high-latitude regions, a subset of the global daily data, about 4000 stations located north of 45° N with data records longer than 20 years during 1973–2003, has been created. Yang et al. (2005) applied a consistent procedure derived from the WMO Solid Precipitation Intercomparison (SPICE; Goodison et al., 1998), using wind speed, temperature, and precipitation as inputs (Yang et al., 1998b, 2005). They quantify the precipitation gauge measurement biases for the wind-induced undercatch, wetting losses, and trace amount of precipitation. For the US stations, wind data from the standard height were reduced to the gauge level of the NWS 8 in. gauge (standard height is 1 m). Wind speeds and directions were measured at the Canadian climatic network; the same approach was applied to estimate the wind speed at the gauge height (standard height is 2 m) on precipitation days. The corrections were done only for those stations with wind observations. Unfortunately there are many stations in the USA without wind information, and this is a challenge to gauge bias corrections.

This study uses the updated (until 2013) monthly precipitation, temperature and wind speed data from Yang et al. (2005) for the selected AK and YK stations (Table 1). The selected data periods range from 7 to 10 years for the stations, which is considered long enough to examine precipitation patterns in these regions. Missing records affect regional climate data analyses. In this study, a threshold of 0 °C of monthly temperature has been used to determine the cold and warm months for snow and rain. Mixed precipitation has not been classified separately. The frequency of missing values was calculated when the bias correction was made in Yang et al. (2005). Any month with fewer than 20 days (∼ 30 %) of measurements is excluded from data analysis. Statistical methods to compare the measured and corrected monthly and yearly precipitation data across the selected border station pairs is used to analyse these data. It also carries out regression analysis on monthly precipitation records and calculates the cumulative precipitation amounts to derive the double mass curves (DMCs) over the study period. The DMC is a useful tool to evaluate the consistency of observation records over space and time (Searcy and Hardison, 1960). Some typical issues of observations that DMCs can identify include changes in the station location and in-

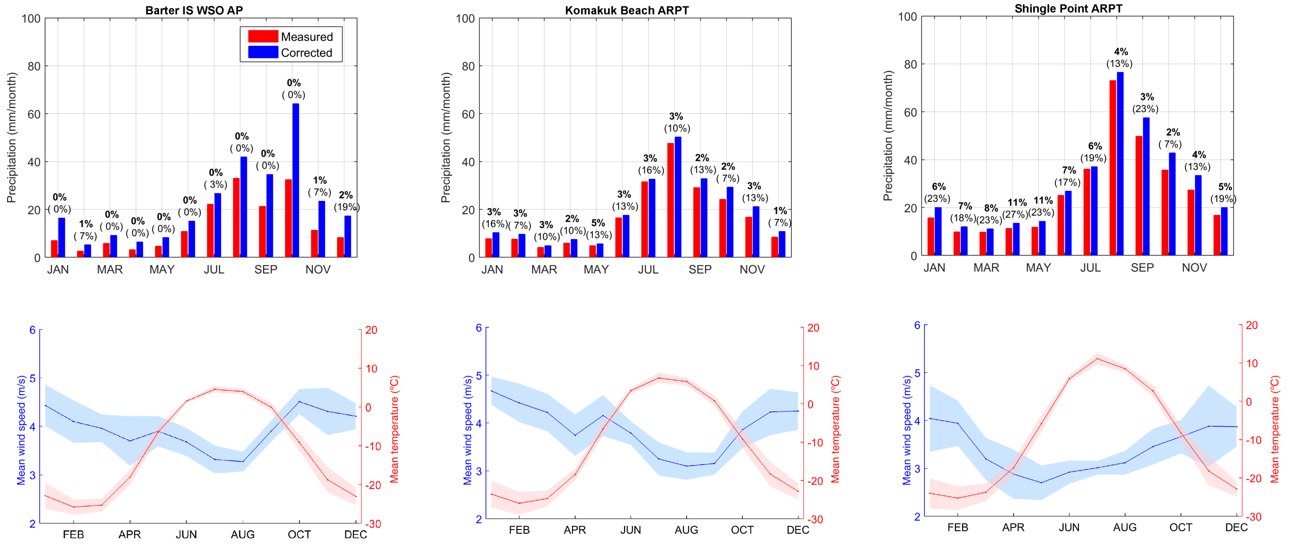

Figure 2. Monthly mean precipitation at three stations during 1977–1988 (upper panels) and corresponding monthly mean wind speed and air temperature (bottom panels). Shadows represent the 95 % confidence interval for the temperature and wind speed. The percentages above the bars represent the missing data for the corresponding time step. The bold percentage is the monthly mean, and the one in the parentheses is the maximum missing value in the study period.

struments or sensors. A reference station is needed for DMC analyses. In this study, the DMC has been applied without a reference station to mainly detect any shifts between the observed and corrected precipitation. Through the data analyses and comparisons with other studies, we document the spatial and temporal variations of bias corrections across the border stations. We also determine the precipitation gradients across the border and examine the changes, due to the bias corrections of the US and Canadian gauge data, in precipitation distributions on both seasonal and yearly timescales.

3 Results

Based on the analyses of the measured precipitation (P_m) and corrected precipitation (P_c) data, this section presents the results on the bias corrections of monthly and yearly precipitation for each station, regression and correlation of monthly precipitation data between the stations, and cumulative precipitation via the double mass curves for the warm (monthly temperature > 0 °C) and cold seasons (monthly temperature < 0 °C).

3.1 Monthly data and corrections

The monthly mean precipitation and bias corrections are illustrated in Fig. 2 for the northern group during the corresponding observation period (Table 1). In Fig. 2, the missing data percentages are also presented for each month. Barter Island had the lowest percentages of missing data, about 2 % as a maximum monthly mean in December. The mean missing percentages for the Komakuk station was about 5 % (in May), with the maximum month in July 1984 (16 %). For Shingle Point, the mean missing values were 11 % for both April and May, with the maximum (26 %) in April 1979. Given the small percentages of missing records, its impact is insignificant on monthly mean and yearly precipitation calculations. Figure 2 shows that annual precipitation cycle was centred on August, with an approximate maximum P_m around 40 to 80 mm between August and September. This maximum was coincident with the monthly mean maximum temperature in the area (around 10 °C).

For the Barter Island station in AK, the corrections were variable through the months. The monthly corrections increased the P_m amount by 3–31 mm for snow to 4–9 mm for rain. The relative increases were 59–136 % for snow and 20–41 % for rain, with a monthly mean of 9 mm (or 76 %). The relative changes were usually large for months with low P_m and small for months with high precipitation. In other words, the monthly correction amounts did not always match the percentage changes; i.e. a small correction in a dry month can have a large percentage change.

It is important to note that gauge measurements at Barter showed the maximum precipitation in August, but the peak shifted to October due to the corrections; i.e. the mean monthly P_c in October were 98 % (about 32 mm) more than the P_m (Fig. 2). Closer examination of the monthly precipitation time series for Barter Island (Fig. 3) indicated that, for most of the years, October was the most significant contributor to the total annual (23 % for P_m and 22 % for P_c). However, there were some years in the study period with the maximum P_m in other months; for example, the highest P_m in 1982 was in September, as documented by Yang et al. (1998b). Climate data and analyses showed

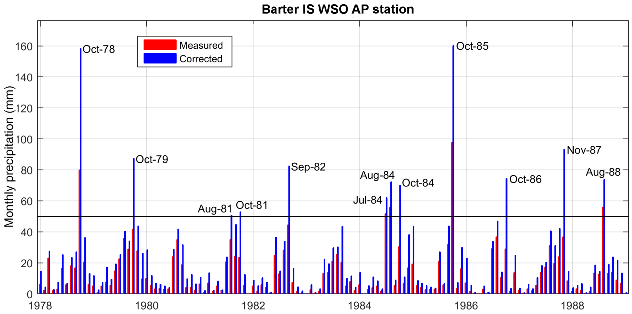

Figure 3. Monthly precipitation records at the Barter station during 1978–1988. The months with more than 50 mm (black line) are labelled.

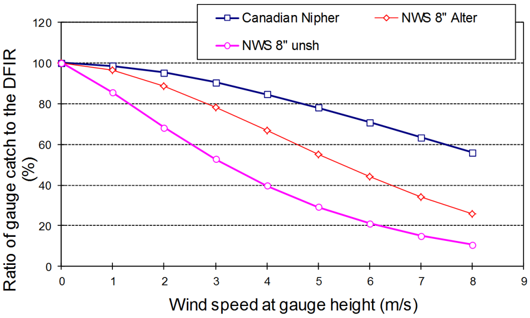

Figure 4. Comparison of the catch ratio of snowfall as a function of wind speed at gauge height for the Alter-shielded or unshielded NWS 8 in. standard gauge and the Canadian Nipher snow gauge. DFIR is the Double Fence Intercomparison Reference (Yang et al., 1998)

the highest wind speed (4.5 m s^{-1}) and cold temperature (about −9 °C) for October, indicating higher undercatch by the US standard gauge for snowfall. On the other hand, the wind speed showed the minimum values in July and August (3.3 m s^{-1}), coincident with the highest temperatures (4.6 and 4 °C) (Fig. 2). Due to the combination of warm temperatures and low wind speeds, the corrections for summer months were the lowest at this station (20–27 %).

For the Komakuk Beach station in Yukon, the corrections increased the precipitation by 0.7–5.5 mm (or 14–34 %) for snow and 1–2.6 mm (4–10 %) for rain, with a total monthly mean change of 2.6 mm (14 %) (Fig. 2). The monthly maximum precipitation was in August, i.e. 48 and 50 mm, respectively, for the P_m and P_c. The monthly minimum precipitation was in March, i.e. $P_\mathrm{m} = 4.2$ mm and $P_\mathrm{c} = 5$ mm. For this station, the extremes remained in the same month after the bias corrections. The wind speed had the minimum value in August (3.1 m s^{-1}) and September (3.2 m s^{-1}), and maximum in December (4.3 m s^{-1}) and January (4.7 m s^{-1}). The temperatures were highest in July (6.9 °C) and August (5.8 °C), and lowest in February and March (−25 °C). Given this climate condition, the corrections were lower in the summer months (mean of 6 %) and higher in winter (mean of 23 %).

The monthly corrections for the Shingle Point station in Yukon ranged from 1–7.6 mm (3–15 %) for rain to 1–8.2 mm (14–28 %) for snow, with the monthly mean correction of 4.2 mm (14 %). The maximum precipitation was in August, about 73–76 mm (or 20 % of the annual total) (Fig. 2). The minimum precipitation was in March, with 9.8 mm for P_m and 11 mm for P_c. The monthly wind speeds were generally higher in winter and lower in summer, with the maximum in February (4 m s^{-1}) and minimum in May (2.7 m s^{-1}). The temperatures had a common annual cycle with the maximum in July (11 °C) and the minimum in February (−24.3 °C). Because of the higher wind speeds and cold temperatures in the cold months, the corrections were greater for the winter season.

It was necessary to compare the correction result across the border in order to quantify the effect of biases in gauge observations on precipitation analyses, such as precipitation distribution and seasonal patterns. The mean snowfall corrections were about 96 % for Barter Island in Alaska and around 22 % for both Shingle Point and Komakuk stations in Yukon; while the rainfall corrections were approximately 32 % for Barter and 7 % for the two Yukon stations. Bias corrections also demonstrated a clear shift in the maximum precipitation timing for the Barter Island, but no change for the Yukon stations. This remarkable contrast across the border was caused mainly by the difference in gauge types and their catch efficiency. Many experimental studies have shown that the Canadian Nipher snow gauge catches more snowfall relative to the US gauge (Goodison et al., 1998; Yang et al., 1998b). For instance, the mean catch ratios for snowfall were about 40 and 85 % for 4 m s^{-1} wind speed, respectively, for the NWS 8 in. unshielded and Nipher gauges (Fig. 4) (Yang et al., 1998b).

For the central group, the maximum and minimum P_m were in July and March for the Eagle station, respectively (Fig. 5). The corrections did not modify the timings of maximum and minimum amounts; they remained in July for the maximum ($P_\mathrm{m} = 67$ mm and $P_\mathrm{c} = 70$ mm) and in March for the minimum ($P_\mathrm{m} = 3$ mm and $P_\mathrm{c} = 4$ mm) precipitation. The correction increased the precipitation by 0.6–1.8 mm (8–22 %) for snow and 1–3 mm (5–10 %) for rain, with a monthly mean correction of 1.7 mm (12 %). The annual temperature cycle for Eagle showed warmer temperatures relative to the northern station, with the maximum of 16.2 °C and above 0 °C during April to mid-October. Eagle had lower wind speeds around 1 m s^{-1} (Fig. 5).

For Dawson station, precipitation was more homogeneous throughout months, varying from 10 mm in October to 50 mm in June. Another relative maximum occurs in January with $P_\mathrm{m} = 38$ mm (Fig. 5). The precipitation correction was small and fluctuated from 0.3 to 1 mm (or 2–4 %) for snow and 0.4–1.3 mm (3–4 %) for rain. This small correction

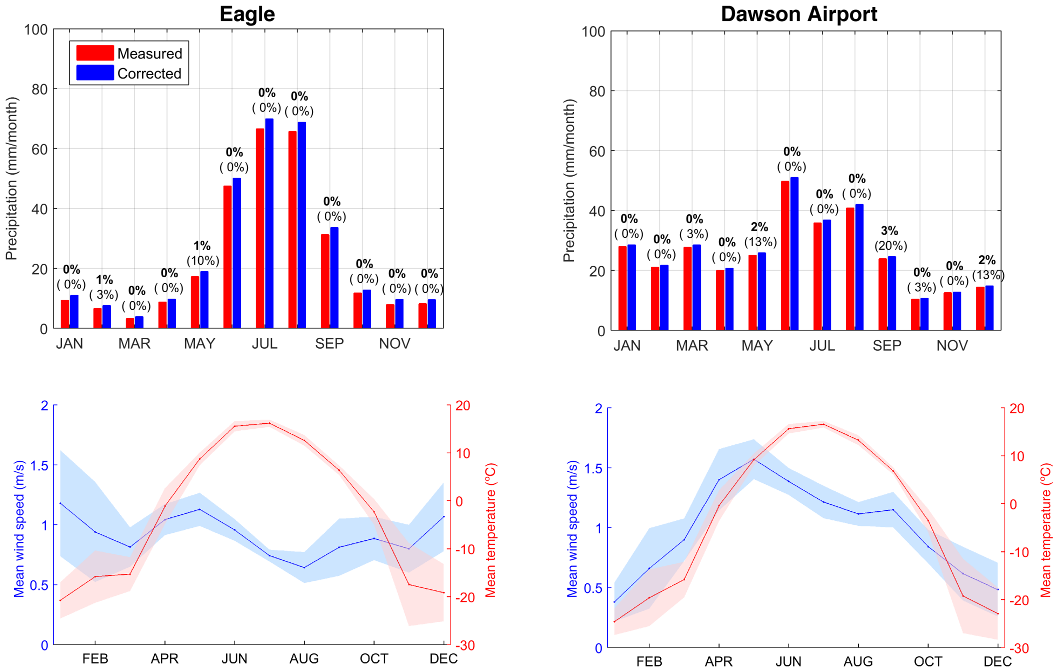

Figure 5. Monthly mean precipitation at two stations during 2006–2013 (upper panels) and corresponding monthly mean wind speed and air temperature (bottom panels). Shadows represent the 95 % confidence interval for the temperature and wind speed. The percentages above the bars represent the missing data for the corresponding time step. The bold percentage is the monthly mean, and the one in the parentheses is the maximum missing value in the study period.

was due to the lower undercatch correction for the Nipher gauge, besides the warmer temperatures and lighter winds. The temperature annual amplitude was between 16 °C in July and −25 °C in January, with temperatures above 0 °C from April to September. Wind speeds showed a clear annual cycle with the maximum in May (1.6 m s^{-1}) and lighter winds in winter months, with the minimum in January (0.4 m s^{-1}).

The temperature and wind conditions were similar between the Eagle and Dawson stations, with mean temperature around 1 °C and wind speed of 1 m s^{-1}. The missing data percentages were also similar for Eagle and Dawson stations: less than 3 % for most months, with the maximum of 10 % in May 2006 for Eagle and 20 % in September 2009 for Dawson. The bias corrections were quite different, with the mean corrections of 16 % for snow and 7 % for rain at Eagle, and about 2 and 3 % for both rain and snow at Dawson. Overall, the correction was 4 times greater at Eagle than that at Dawson. This discrepancy reflects again the catch difference between the US and Canadian standard gauges.

In order to understand the effect of precipitation bias corrections on regional climate around the AK–YK border, it was useful to examine and compare the temperature and precipitation features between the northern and central regions. The monthly mean temperature threshold of 0 °C did not occur exactly at the same time among the two groups; the warm months (above 0 °C) were between June and September in the north group and between April and September in the central group. Although both regions had similar mean minimum temperatures, around −24 °C and −27 °C, the maximum temperature was considerably lower in the north part, with the average of 8 °C in the north group vs. 16 °C for the central region. Additionally the monthly mean wind speed was higher for the northern region, 4 vs. 1 m s^{-1}. Therefore, because of the colder temperatures and higher winds in the northern region, the bias corrections were higher in the north relative to the central region.

3.2 Yearly data and corrections

The annual P_m and P_c time series for 11 years during 1978–1988 in the northern group is presented in Fig. 6. There were almost no missing data for the whole period, except 3 % for 1978. At the Barter Island station in Alaska, the yearly P_m ranged from 114 to 211 mm, with a long-term mean of 155 mm. The mean annual corrections ranged from 67 to 138 mm, with a long-term mean of 101 mm (or 65 %). The P_c records varied from 181 to 343 mm. The maximum precipitation was in 1985 for both P_m and P_c (211 and 343 mm, respectively). The minimum precipitation was in 1983 for the P_m and P_c (114 and 181 mm, respectively).

For Komakuk Beach station in Yukon, the P_m ranged from 103 to 306 mm, with the missing data between 0 and 7 % among the years. The bias corrections increased the precipitation by 13 to 45 mm (or 8–19 %). The long-term mean was

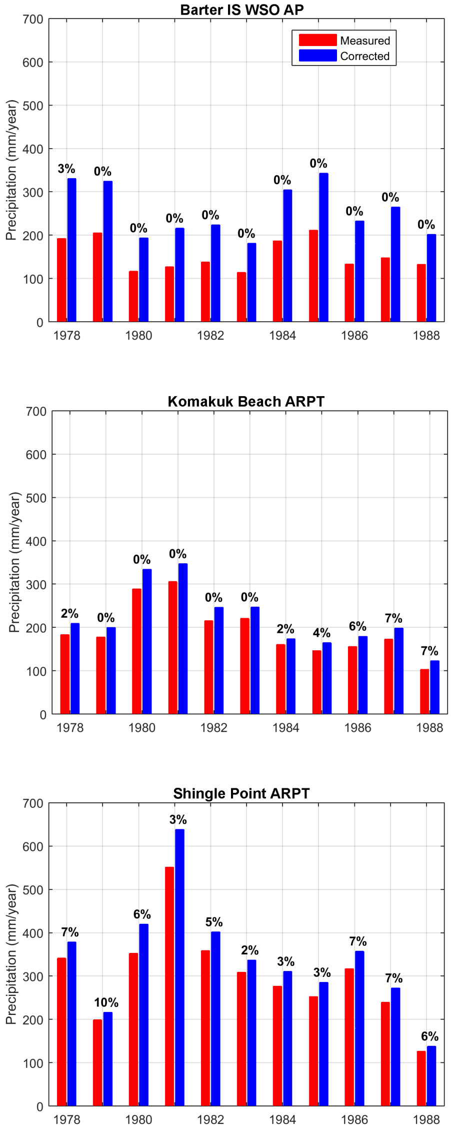

Figure 6. Annual precipitations during 1978–1988 for the three stations in the northern group across the border. The percentages above the bars represent the missing data for the corresponding year.

about 194 mm for P_{m} and 220 mm with the corrections. The maximum precipitation occurred in 1981: 306 and 347 mm for P_{m} and P_c, respectively. The minimum precipitation was in 1988 for both the P_{m} and P_{c}: 103 and 123 mm, respectively.

For Shingle Point station in Yukon, yearly P_{m} varied from 126 to 551 mm and the P_{c} ranged from 138 to 638 mm. The mean annual total precipitation was about 302 mm for P_{m} and 341 mm after the corrections (change of 13 %). The high and low extreme years were 1981 ($P_{\mathrm{m}} = 551$ mm, $P_{\mathrm{c}} = 638$ mm) and 1988 ($P_{\mathrm{m}} = 126$ mm, $P_{\mathrm{c}} = 138$ mm). Shingle station had missing data from 2 % in 1983 to 10 % in 1979.

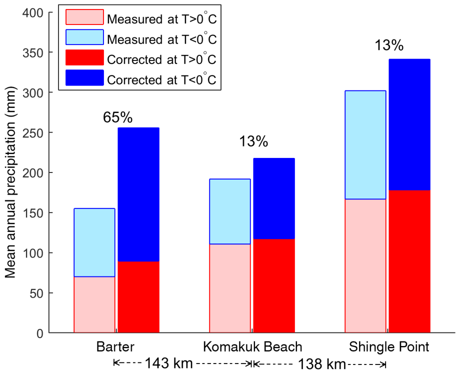

Figure 7. Mean annual (1978–1988) measured and corrected precipitation for cold ($T < 0$ °C) and warm ($T > 0$ °C) months. The percentages are the changes from measured to corrected precipitation. The approximate horizontal distance between the stations is displayed at the bottom.

Figure 7 displays the mean annual precipitation in cold and warm seasons for the northern group. The gauge measurements showed annual values from 155 mm at Barter Island and 194 mm at Komakuk to 302 mm at Shingle Point, i.e. a strong precipitation increase from the west to the east, particularly between Komakuk Beach and Shingle Point. However, the corrected data (P_{c}) showed a different pattern (Fig. 7), i.e. higher precipitation at Barter than Komakuk, so the gradient across the border changed the sign and magnitude. This change was caused mainly by the high correction at the Barter station, particularly for snowfall data during the cold months (Fig. 2).

For the central group, the annual results are shown for 8 years (2006–2013) in Fig. 8. The P_{m} ranged from 66 to 391 mm at Eagle, and the bias corrections were 5–27 mm, correspondingly, which on average increase the total precipitation by 7 %. At Dawson, the P_{m} ranged from 158 to 333 mm, and the adjustments were from 4 to 10 mm, with an average increase in yearly precipitation by 3 %. The gauge data showed a slight increase (12 mm) of mean precipitation from west to east, i.e. slightly higher P in Yukon relative to Alaska. This result is consistent with other studies (Simpson et al., 2002, 2005). The corrected data, on the other hand, suggest a smaller gradient (1 mm) across the border (Fig. 9). This change was mainly due to the higher corrections for the US 8 in. gauge at Eagle.

Similar to the monthly results, the northern stations exhibited higher yearly corrections for snowfall and rainfall measurements relative to the central group. This was because of higher winds in the northern stations, i.e. yearly mean wind speeds of 3.8 m s^{-1} in the north group and 1 m s^{-1} in the central group. This windy and snowy environment in the north produced higher wind loss for the snowfall measurements by the gauges, which were the largest errors in precipitation records in the high latitudes (Benning and Yang, 2005; Yang

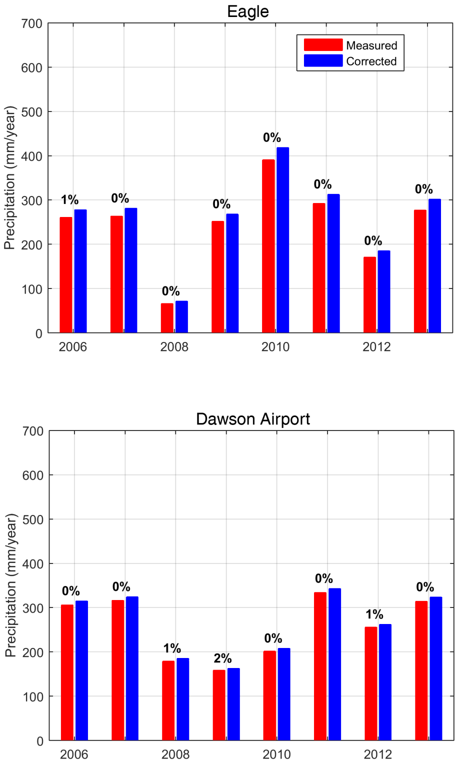

Figure 8. Annual precipitations during 2006–2013 for two stations in the central part of the AK–YK border. The percentages above the bars represent the missing data for the corresponding year.

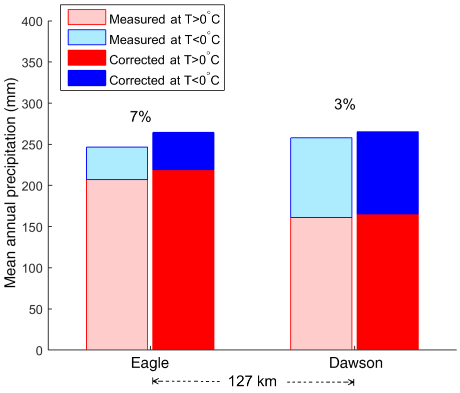

Figure 9. Mean annual (2006–2013) measured and corrected precipitation for cold ($T < 0\,^{\circ}$C) and warm ($T > 0\,^{\circ}$C) months. The percentages are the change from measured to corrected precipitation. The approximate horizontal distance between the stations is displayed at the bottom.

and Ohata, 2001; Yang et al., 1998b). It is important to note that gauge-measured and bias-corrected data showed different pattern in seasonal and yearly precipitation in the northern region. In other words, bias corrections of gauge measurements alter the precipitation gradient in the northern areas; this change was mainly due to the difference in the catch efficiency between the US and Canadian standard gauges. The corrections for the US gauge snow measurements were much higher than the Canadian gauge, particularly in the cold and windy coastal regions.

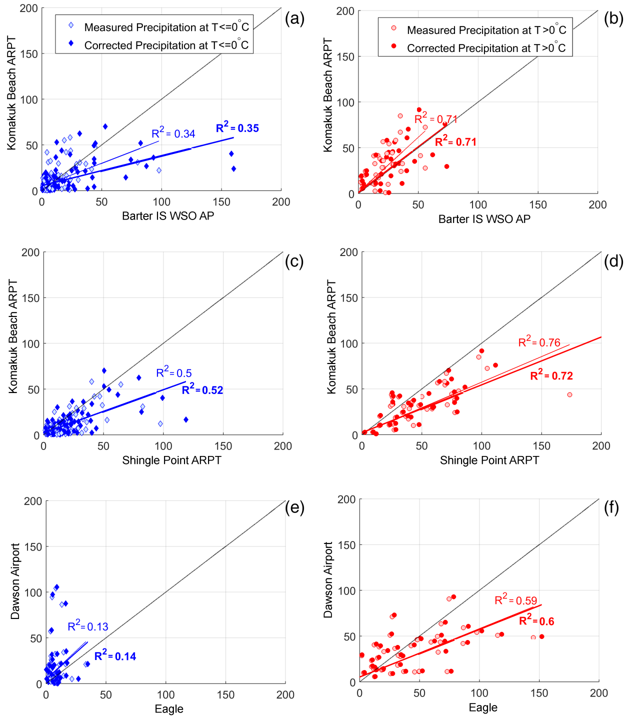

Figure 10. Scatter plots between station pairs for the measured and corrected precipitation (mm). The red colour shows warm months and the blue represents the cold months. **(a)** and **(b)** – Barter and Komakuk comparison across the border; the highest corrected values for Barter (AK) are labelled with the date to compare with Fig. 4c and d – Komakuk and Shingle Point comparison within Canada. **(e)** and **(f)** – Eagle vs. Dawson across the border for the central group.

3.3 Regression analysis of monthly data

The scatter plots of corresponding monthly precipitation for the two stations across the border and between the two Yukon stations in Canada are illustrated in Fig. 10. For the cold season (Fig. 10a), the gauge data showed more snowfall at Barter for most years. Regression analysis suggested a weak relationship, with $R^2 = 0.34$. The corrected data showed a similar relationship, but a shift in the regression line, indicating a greater precipitation difference over the cold season across the border. For the warm season (Fig. 10b), the gauge data showed higher precipitation at the Komakuk station, and the regression suggested a much stronger relationship. The corrected data revealed a closer relationship between these two stations, proposing a smaller gradient for the warm months.

The scatter plot between the two stations in the Yukon Territory showed higher precipitation at Shingle Point for both cold and warm seasons. It also gave another point of view about the effect of the correction in this area. Relative to the cold months (Fig. 10c), the corrections were smaller for the warm months (Fig. 10d), and correlation improved ($R^2 = 0.72$–0.76). However, the relationship did not change much in both cases between the measured and corrected data. This was because of the very small amount of corrections for the lower wind conditions and higher catch efficiency of the Canadian Nipher gauge.

For the central group, the scatter plot between Eagle and Dawson stations illustrated a clear difference in precipitation amount for the cold and warm months (Fig. 10e–f). The cold months showed more precipitation at Dawson, particularly for the wettest events, while Eagle did not show any comparable amount. The correlation was weak and insignificant ($R^2 = 0.13$). The shift in the fit line between measured and corrected data was also very small. The warm months showed low precipitation at Dawson: a different pattern from the cold months. The regression was better, $R^2 = 0.59$ with a smaller shift due to the corrections.

Overall, we obtained consistent results among the Alaska and Yukon stations. The correlations were higher in warm months ($R^2 = 0.58$ to 0.76) and lower for the cold season (R^2 between 0.13 and 0.52). This result may suggest that the rainfall was more homogeneous over the regions in summer, and greater difficulty and errors in snowfall measurements during the cold months.

3.4 Cumulative precipitation via DMCs

The DMC plot for Barter Island and Komakuk Beach showed more P_m at Komakuk than Barter (Fig. 11a). The bias corrections led to a shift of the relationship with a significant increase in the total precipitation amount at Barter. Relatively, the total cumulative precipitation for Barter Island increased by 65 % after the correction and by 14 % at Komakuk. The difference between the two stations at the last cumulative point (December 1988) is 426 mm for P_m and 393 mm for P_c. This shift represented a modification in the precipitation difference between these stations, i.e. a change in the gradient's direction (Fig. 7).

The comparison of cumulative precipitation values between Shingle Point and Komakuk, both in Yukon, is illustrated in Fig. 11b. Shingle Point showed more cumulative precipitation at the end of the period ($P_\mathrm{m} = 3322$ mm vs. $P_\mathrm{m} = 2115$ mm for Komakuk). Although the relationship was more homogeneous between these stations, there was a break in the records around 1300 mm for Komakuk, maybe associated with changes in instruments or sensors. Examination of the station history and information revealed an anemometer issue around the critical time that was fixed by August 1980. This may affect wind data and thus the corrected precipitation values. Both stations showed increases in total cumulative precipitation by 13 %.

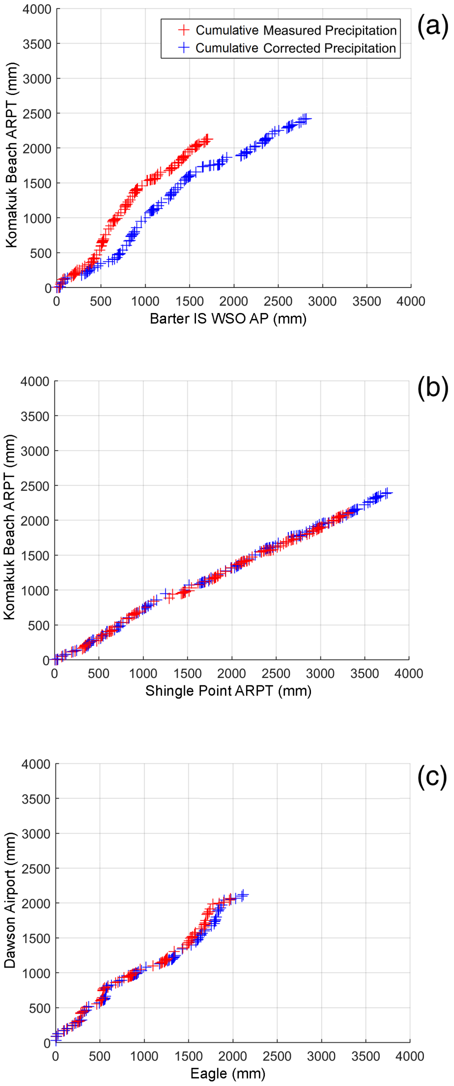

Figure 11. Double mass curves between station pairs. The red colour shows the warm months, and blue represents the cold months. The top and the central plots compare the stations for the northern group, and the bottom one is the central station comparison across the border.

The central stations showed a greater amount of P_m in Dawson (2065 mm) than in Eagle (1973 mm) over the study period. Bias corrections changed the total precipitation by 3 and 7 % for Dawson and Eagle, respectively, resulting in a shift in the DMC (Fig. 11c), particularly for the last period of time, to 2123 mm in Dawson and to 2116 mm in Eagle. This shift also represented a slightly smaller precipitation difference between the two stations. During the 8 years, the cumulative difference decreased from 92 to 7.3 mm.

In summary, the DMC for measured and corrected precipitation showed that the main change was due to the difference in their corrections (Fig. 11); the north stations showed a greater change compared with the central group. The P_c showed in all the cases a smaller precipitation difference between the two countries. This smaller difference led to a decrease in the precipitation gradient across the border. This result implies that existing precipitation climate maps and information derived from gauge measurement without bias corrections may overestimate the precipitation gradient in these regions. This overestimation will affect regional climate and hydrology analyses.

4 Summary and discussion

This study documents and quantifies the inconsistency in precipitation measurements in the northern and central regions of Alaska/Yukon, with a focus on station pairs across USA–Canada border. The monthly bias corrections show large errors in the gauge records due to the windy and cold environment in the northern areas of Alaska and Yukon. The corrections for gauge undercatch increase the snowfall by 136 % in January for Barter Island station in Alaska. For the Yukon stations, the increase is about 31 % in January and 4 % in July. These represent an annual mean loss of 81 mm (101 %) in snowfall and 20 mm (29 %) of rain at Barter, while at Shingle Point and Komakuk Beach in Yukon the corrections are, on average, about 25 mm (21 %) for snow and 8 mm (6 %) for rain. For Eagle (AK) and Dawson (YK) stations in the central region, the bias corrections are small. The monthly corrections range from 2 to 22 % in winter and from 3 to 10 % in summer months.

On the annual scale, Barter Island station in AK shows a yearly mean correction of around 65 %, 5 times greater than the correction at Shingle Point and Komakuk Beach (13 and 14 %) in Canada. In the central region, Eagle station shows an increase by 7 %, meanwhile for Dawson the increase is only 3 %. Thus, the bias correction for Alaska is twice that of the Yukon stations. Relative to the northern region, these corrections are small mainly due to warmer temperatures and lower winds in the central region. These results clearly demonstrate that bias corrections may affect the spatial distribution of precipitation across the border.

Regression analyses of the monthly data show small changes in the relationship due to the bias corrections. The most evident change in the regression is between Barter Island and Komakuk Beach for both warm and cold seasons. The rest of the scatter plots, for Komakuk Beach–Shingle Point and Eagle–Dawson, do not show any appreciable change as the result of the bias corrections. There is a stronger precipitation correlation for the warm months (mainly rainfall) than for the cold month (mainly snowfall) for all the station pairs. The cold months seem to have greater precipitation variability across the regions.

The double mass curve analyses demonstrate a significant change in the precipitation accumulation and difference between the two stations across the AK–YK border for the northern region, little changes for the two stations in Yukon, and a smaller change in the central group. These changes, caused by gauge catch efficiency, alter the precipitation difference, resulting in a smaller and inverted precipitation gradient across the border in the northern region. The DMC is a useful tool for evaluating the consistency of observation records over space and time (Searcy and Hardison, 1960). Although in this work the DMC has not been constructed against a reference station, the results clearly show some breaks on the slope and gaps in the curves, indicating changes in precipitation relationship across the border that could be caused by any of the two stations. This information provides the timing when significant changes occurred in the precipitation regime. Detailed metadata and information for the stations/networks are necessary to understand the changes in precipitation observations and to improve the homogenization of the precipitation records over the high latitudes.

This study shows similar monthly P_m across the north border region and higher P_m in Yukon than Alaska over the central region. This result is similar to other studies (Serreze and Hurst, 2000; Simpson et al., 2005). After the bias corrections, precipitation patterns across the border changed, i.e. higher precipitation in Barter than Komakuk, or, in other words, an inverted gradient across the borderline. Over the central region, the measured mean annual precipitation is slightly higher in Yukon than Alaska, which is also consistent with Simpson et al. (2002, 2005). Our results suggest that the gradient between the central pair of stations becomes smaller after the bias correction. This discrepancy should be taken into account when using the precipitation data across the national borders for regional climate and hydrology investigations.

Missing data may affect regional precipitation analyses. In this study, we calculated the missing data percentages for all stations during the corresponding study periods and set up a threshold of 30 % to exclude those months with higher missing values from monthly precipitation calculations. We compared the precipitation amounts with and without the application of the threshold. The results do not show any significant changes in the differences of gauge-measured annual mean precipitation across the border, although this filter affected annual precipitation in certain years. For instance, the northern station pair (Barter and Komakuk stations) has missing value of 32 % in July 1987. Calculations of yearly precipitation for 1987 with and without this month show 16 and 10 % difference at Komakuk and Barter Island stations, respectively. Over the study period of 11 years, the annual mean bias correction percentages remain the same (65 % in Barter and 13 % in Komakuk) with or without the missing months. The mean annual decrease in bias correction amounts after the consideration of missing data is about 1–3 % in the northern region. This analysis suggests that the effect of missing data for our study is not significant, particularly with the application of a 30 % missing threshold. More efforts are needed to further examine the issues of missing records in climate analyses.

Classification of precipitation types is the first step for the bias corrections of gauge records. It is also important for climate change analyses over the cold regions. Leeper et al. (2015), in comparison of USCRN with the COOP station network precipitation measurements, averaged the USCRN hourly temperature data during precipitation periods into an event mean and used it to group precipitation events into warm (mean temperature $> 5\,^{\circ}\mathrm{C}$), near-freezing (mean temperature between 0 and $5\,^{\circ}\mathrm{C}$), and freezing (mean temperature $< 0\,^{\circ}\mathrm{C}$) conditions. Yang et al. (2005) used the daily mean air temperature to estimate precipitation types (snow, mixed, and rain) when this information was not available for the northern regions. In this study, monthly mean temperatures have been used to determine the warm months (mainly for rain) and cold months (mainly for snow). Mixed precipitation has not been classified separately. This approach is reasonable for our analysis to focus on the inconsistency in the monthly and yearly P_m records across the border. Data collections and analyses on shorter timescales, such as daily or hourly steps, are expected to produce better results, since temperatures vary throughout the days in a month, particularly in the spring and fall seasons. Automatic sensors will also be important to decide precipitation types at the operational and research networks.

The bias-corrected precipitation data set developed by Yang et al. (2005) has been used for this analysis. The corrections have been done systematically on a daily timescale that affects the daily P_m time series. This analysis focuses on the results of monthly and yearly precipitation data and quantifies the changes in precipitation pattern across the AK–YK border. Careful analyses of available daily measured P_m and corrected P_c data are necessary, since in the northern regions with low precipitation in winter the bias corrections can easily increase the daily P_m by a factor of up to 4–5 (Benning and Yang, 2005; Kane and Stuefer, 2015; Yang et al., 1998b, 2005). This means that extreme precipitation events have been very likely and seriously underestimated by using the gauge records without any bias corrections. The consequence is certainly significant for climate regime and change investigations. To fill this knowledge gap, our efforts are underway to examine the daily corrections, particularly on the windy and heavy-precipitation days, and to document the possible underestimation of precipitation extremes over the large northern regions.

Automation of the meteorological observation networks and instruments has been a trend over the past few decades around the world, including both developed and developing nations. There is a large variety of automatic gauges currently used for precipitation measurements at the national networks (Nitu and Wong, 2010). These gauges differ in the measuring system, orifice area, capacity, sensitivity, and configuration. The variation in automatic gauges is much greater relative to the manual standard gauges (Goodison et al., 1998; Sevruk and Klemm, 1989). As demonstrated by Yang et al. (2001) and this study, the use of different instruments and configurations significantly affect the accuracy and consistency of regional precipitation data. Fortunately, the Geonor gauge has recently been chosen and used at both the US Climate Reference Network and the Surface Weather and Climate Network (SWCN) in Canada. This may reduce the inconsistency in precipitation measurements across the USA–Canada border, although the double and single Alter windshields have been installed with the Geonor gauges in the USA and Canada, respectively.

Finally, it is important to emphasize that automatic gauges also significantly under-catch snowfall (Wolff et al., 2015), and bias corrections are necessary in order to obtain reliable precipitation data for the cold regions and seasons. The WMO SPICE project aims to examine the performance of automatic gauges and instruments for snowfall observations in various climate conditions. It has tested many different automatic gauges, including the Geonor gauge, at more than 20 field sites around the globe (Nitu et al., 2012; Rasmussen et al., 2012; Wolff et al., 2015). The results of this project will be very useful to improve precipitation data quality and regional climate analyses, including the border regions between the USA and Canada.

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