The Cryosphere Discuss., 9, 3709–3739, 2015
www.the-cryosphere-discuss.net/9/3709/2015/
doi:10.5194/tcd-9-3709-2015

The Cryosphere Discussions
Open Access

Inconsistency in precipitation measurements across Alaska and Yukon border

L. Scaff[1], D. Yang[2], Y. Li[1], and E. Mekis[3]

[1]Global Institute for Water Security, University of Saskatchewan, Saskatoon, SK, S7N 3H5, Canada
[2]National Hydrology Research Center, Environment Canada, Saskatoon, SK, S7N 3H5, Canada
[3]Environment Canada, Toronto, ON, Canada

Received: 08 June 2015 – Accepted: 17 June 2015 – Published: 16 July 2015

Correspondence to: Y. Li (yanping.li@usask.ca)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 (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 135 % in January, 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 US and Canada border. This discontinuity is greater for snowfall than for rainfall, as gauge snowfall observations have large errors in the windy and cold conditions. This result will certainly impact regional, particularly cross borders, 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-inch gauge is used for precipitation measurements in the US, and the Nipher snow gauge is the

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

standard instrument over Canada. Different instruments have also been used in various observational networks within the same country. The Type-B rain gauge and Nipher gauge are the standard instruments for rain and snow observations in Canada, respectively (Mekis and Vincent, 2011; Metcalfe and Goodison, 1993), and recently the Geonor gauges have been installed at the synoptic stations across Canada.

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 P discontinuity within a country (Groisman and Easterling, 1994; Sanderson, 1975). Leeper et al. (2014) found that the US COOP 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 USCRN. Conversely, wetting and evaporation losses, which dominate in summer, were sources of bias for USCRN. Yang and Simonenko (2013) compared the measurements among 6 Russian Tretyakov gauges at the Valdai experimental station, and reported the 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-inch gauges, under measure 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-inch 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

TCD
9, 3709–3739, 2015

discontinuity in precipitation records between the US and Canada borders particularly in windy and cold regions. Differences in the snow measurements across the US and Canada border has also been noticed in other studies as a problem to produce gridded products and to develop P input for basin hydrological study (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.

The objective of this work is to examine the inconsistency in precipitation measurements across the border between Alaska and Yukon. We analyze 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.

2 Study area, data and methods

The study areas include the northern and central regions of Alaska (AK) and Yukon (YK). We choose 5 climate stations across the Yukon and 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 in 2 groups. The first group, 3 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, i.e. the Eagle station in Alaska and Dawson station in Yukon, about 130 km apart. These stations have been operated by the NWS and Environment Canada (EC) since the early 1970's. The observations have been done according to the national standards of US and Canada. The detail information for these stations are given in Table 1, such as the location, period of measurement, instrument types for precipitation observations, and a climate summary for yearly temperature, precipitation (P), and wind speed.

Yang et al. (2005) have developed a bias corrected daily precipitation dataset for the northern regions above 45° N. The source data are acquired from the National Climatic Data Center, i.e. a global daily surface data archive for over 8000 stations around the world (http://www1.ncdc.noaa.gov/pub/data/gsod/readme.txt). To focus on the high latitude regions, a subset of the global daily data, about 5000 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 (Goodison et al., 1998), using wind speed, temperature, and the precipitation as inputs (Yang et al., 1998b, 2005), at all the stations over the high latitude regions. They quantify the precipitation gauge measurement biases for the wind-induced undercatch, wetting losses, and trace amount of precipitation. This study uses the updated monthly precipitation, temperature and wind speed data from Yang et al. (2005) for the selected AK and YK stations. The data periods range from 7 to 10 years for the stations, but long enough to examine P patterns in these regions.

This study applies statistical methods to compare the measured and corrected monthly and yearly precipitation data across the border station pairs. It also carries out regression analysis on monthly P records, and calculates the cumulative P amounts to derive the double mass curves over the study periods. 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 time scales.

TCD
9, 3709–3739, 2015

3 Results

Based on the analyses of the measured precipitation (Pm) and corrected precipitation (Pc) data, this section presents the results on the bias corrections of monthly and yearly precipitation for the stations, regression and correlation of monthly P 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 P and bias corrections are illustrated in Fig. 2 for the northern group during the corresponding observation period (Table 1). The annual P cycle is centered on August, with an approximate maximum P around 40 to 60 mm between August and September. This maximum is coincident with the monthly mean maximum temperature in the area (around 10 °C).

For the Barter Island station in AK, the corrections are variable through the months. The monthly corrections increase the P amount by 3–34 mm for snow to 4–9 mm for rain. The relative increases are 59–136 % for snow and 20–41 % for rain, with a monthly mean of 9 mm (or 78 %). The relative changes are usually large for months with low P and small for months with high precipitation. In other word, the monthly correction amounts do not always match with 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 show the maximum P in August and October, but the peak shifted to October due to the corrections; i.e. the mean monthly Pc in October is 100 % (about 70 mm) more than the Pm (Fig. 2). Examination of the monthly P time series for Barter Island (Fig. 3) indicates that, for most of the years, October is the most significant contributor to the total annual (21 % for Pm and 25 % for Pc). However, there are some years in the study period with the maximum Pm in other months; for example, the highest Pm in 1982 was in September, as documented by Yang et al. (1998). Climate data and analyses show the highest wind speed (4.5 $m\,s^{-1}$) and cold temperature (about $-9\,^{\circ}$C) for October, indicating higher undercatch by the US standard gauge for snowfall. On the other hand, the wind speed shows the minimum values in July and August (3.3 $m\,s^{-1}$), coincident with the highest temperatures (4.6 and 4 $^{\circ}$C) (Fig. 2). Due to the combination of warm temperatures and low wind speeds, the corrections for summer months are the lowest at this station (20–27 %).

For the Komakuk Beach station in Yukon, the corrections increase 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 2.4 mm (19 %) (Fig. 2). The monthly maximum *P* was in August, i.e. 47 and 50 mm, respectively, for the Pm and Pc. The monthly minimum *P* was in March, i.e. Pm = 4.2 mm and Pc = 5 mm. These extremes remain the same after the bias corrections. The wind speed has the minimum value in August (3.1 $m\,s^{-1}$) and Sept. (3.2 $m\,s^{-1}$), and max in December (4.3 $m\,s^{-1}$) and January (4.7 $m\,s^{-1}$). The temperatures are highest in July (6.9 $^{\circ}$C) and August (5.8 $^{\circ}$C), and lowest in February and March (–25 $^{\circ}$C). Given this climate condition, the corrections are 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 range from 1–3 mm (3–7 %) for rain to 1–11 mm (14–28 %) for snow, with the monthly mean correction of 3.5 mm (16 %). The month of maximum precipitation is August, about 73–76 mm (or 20 % of the annual total) (Fig. 2). The minimum *P* was in February with 9.2 mm for the measured P; and it shifted to March with 11 mm for the corrected values. The monthly wind speeds are 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 have a common annual cycle with the maximum in July (11 $^{\circ}$C) and the minimum in February (–24.3 $^{\circ}$C). Because of the higher wind speeds and cold temperatures in the cold months, the corrections are greater for the winter season.

It is 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 *P* distribution and seasonal patterns. The mean snowfall corrections are about 100 %

TCD
9, 3709–3739, 2015

for Barter Island in AK and around 22 % for both Shingle Point and Komakuk stations in Yukon; while the rainfall corrections are approximately 32 % for Barter and 6 % for the two Yukon stations. Bias corrections also demonstrate a clear shift in the max P timing for the Barter Island, but no change for the Yukon stations. This remarkable contrast across the border is 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 are about 40 and 85 % for 4 $m\,s^{-1}$ wind speed, respectively, for the NWS 8-in unshielded and Nipher gauges (Yang et al., 1998, Fig. 4).

For the central group, the maximum and minimum Pm is in July and March for the Eagle station (Fig. 5). The corrections did not modify the timings of maximum and minimum P; July for the maximum (Pm = 67 mm and Pc = 70 mm), and March for the minimum (Pm = 3 mm and Pc = 4 mm). The correction increases 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 shows warmer temperatures than in the northern station, around 16.2 °C with temperatures above 0 °C from April to mid-October. Eagle has variable wind speeds around 1 $m\,s^{-1}$ (Fig. 5).

For Dawson station, precipitation is more homogeneous throughout months; varying from 10 to 50 mm in October and June, respectively. Another relative maximum occurs in January with Pm = 38 mm (Fig. 5). The precipitation correction is small and fluctuates from 0.3 to 1 mm (or 2–4 %) for snow and 0.4–1.3 mm (3–4 %) for rain. This small correction is due to the lower undercatch correction for the Nipher gauge, besides the warmer temperatures and lighter winds. The temperature annual amplitude is between 16 °C in July and –25 °C in January, with April to September temperatures above 0 °C. Wind speeds show a clear annual cycle with the maximum in May of 1.6 $m\,s^{-1}$, and lighter winds in winter months with a minimum of 0.4 $m\,s^{-1}$ in January.

The temperature and wind conditions are similar between the Eagle and Dawson regions, with the mean temperature around 1 °C and wind speed of 1 $m\,s^{-1}$. But the

TCD
9, 3709–3739, 2015

bias corrections are quite different, with the mean corrections of 15 % for snow and 6 % for rain at Eagle, and about 2 % for both rain and snow at Dawson. The Eagle correction is four times greater than that for Dawson. This discrepancy reflects again the catch difference between the US and Canadian standard gauges.

In order to understand the effect of P bias corrections on regional climate around the AK–YK border, it is useful to examine and compare the temperature and precipitation features between the northern and central regions. The monthly mean temperature threshold of 0 °C does not occur exactly at the same time among the 2 groups; the warm months (above 0 °C) are between June and September in the north group and between April and September in the central group. Although both regions have similar mean minimum temperatures, around −24 and −27 °C, the maximum temperature is lowers in the north part, average of 8 °C in the north group vs. 16 °C for the central region. Besides, the monthly mean wind speed is 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 are higher in the north relative to the central region.

3.2 Yearly data and corrections

Figure 6 shows the annual Pm and Pc time series for 11 years in the northern group. At the Barter Island station in Alaska, the yearly Pm ranges from 114 to 211 mm, with the long-term mean of 157 mm. The mean annual corrections are about 67–138 mm, with a long-term mean of 101 mm or 65 %. The corrected P records vary from 181 to 343 mm. The maximum precipitation was in 1985 for both Pm and Pc (211 and 343 mm, respectively). The minimum precipitation was in 1983 for the Pm and Pc (114 and 181 mm, respectively).

For Komakuk Beach station in Yukon, the Pm ranges from 103 to 306 mm, the corrections increase the precipitation by 13 to 45 mm (or 8–19 %). The long-term mean is about 197 mm for Pm and 223 mm with the corrections. The maximum P was in 1981, 306 and 347 mm, respectively, for Pm and Pc. The minimum P was in 1988 for both the Pm and Pc, 103 and 123 mm, respectively.

For Shingle Point station in Yukon, yearly Pm varies from 127 to 566 mm, the corrections are 139–88 mm. The mean annual total precipitation is about 306 mm for the gauge data and 345 mm after the corrections (change of 12 %). The high and low extreme years were 1981 (Pm = 566 mm, Pc = 654 mm), and 1988 (Pm = 127 mm, Pc = 139 mm).

According to the gauge measurements, the mean annual *P* in this region fluctuates from 114 mm at Barter, 103 mm at Komakuk to 566 mm at Shingle Point. The gauge data suggest a strong *P* increase from the west to the east, particularly between Komakuk Beach and Shingle Point. However, the corrected data show a different pattern (Fig. 7), i.e. higher *P* at Barter than Komakuk, so the gradient across the border changed the sign and magnitude. This change is caused mainly by the high corrections at the Barter station, particularly for snowfall during the cold months.

For the central group, the results are shown for 8 years (2006–2013) in (Fig. 8). The annual Pm ranges from 100 to 400 mm at the Eagle, and the corrections are 7–27 mm, or 6–9 %, which on average increase the total precipitation by 7 %. While at Dawson, the measured *P* ranges from 158 to 353 mm, and adjustments are 4 mm to 11 mm, with an average increase in yearly precipitation by 3 %. The gauge data show a slight increase (22 mm) of mean *P* from west to the east, but the corrected data suggest a smaller gradient (11 mm) across the border. This change is mainly due to the higher corrections for the US 8-inch gauge at Eagle (Fig. 9).

Similar to the monthly results, the northern stations exhibit higher yearly corrections for snowfall and rainfall measurements relative to the central group. This is 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 produce higher wind-loss for the snowfall measurements by the gauges, which is the largest errors in precipitation records in the high latitudes (Benning and Yang, 2005; Yang and Ohata, 2001; Yang et al., 1998b). It is important to note that gauge measured and bias corrected data show different pattern in seasonal and yearly *P* in the northern region. In other words, bias corrections of gauge measurements alter the

P gradient in the northern areas; this change is mainly due to the difference in the catch efficiency between the US and Canadian standard gauges. The corrections for the US gauge snow measurements are much higher than the Canadian gauge, particularly in the cold and windy coastal regions.

3.3 Regression analysis of monthly data

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

The scatter plot between the two stations in the Yukon Territory show higher P at Shingle point for both cold and warm seasons. It also gives another point of view about the effect of the correction in this area. Relative to the cold months (Fig. 10c), the corrections are smaller for the warm months (Fig. 10d), and there is a better correlation ($R^2 = 0.72$–0.75). However, the relationship does not change much in both cases between the measured and corrected data. This is because very small amount of corrections due to the lower winds and higher catch efficiency of the Canadian Nipher gauge.

For the central group, the scatter plot between Eagle and Dawson stations illustrates a clear difference in precipitation amount for the cold and warm months (Fig. 10e and f). The cold months show more P at Dawson, particularly for the wettest events, while Eagle does not show any comparable amount. The correlation is weak, and insignificant ($R^2 = 0.13$). The shift in the fit line between measured and corrected data is also very small. The warm months show low precipitation at Dawson; a different

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

pattern from the cold months. The regression is better, $R^2 = 0.58$, with a smaller shift due to the corrections.

Overall, we obtain consistent results among the Alaska and Yukon stations. The correlations are higher in warm months ($R^2 = 0.58$ to 0.75) and lower for the cold season (R^2 between 0.13 and 0.52). This result may suggest that the rainfall is more homogeneous over the regions in summer, and greater difficulty and errors in snowfall measurements during the cold months.

3.4 Cumulative precipitation via double mass curves (DMC)

The DMC plot for Barter Island and Komakuk Beach shows more Pm at Komakuk than Barter (Fig. 11a). The bias corrections lead to a shift of the relationship with a significant increase in the total P amount at Bartter. Relatively, the total cumulative precipitation for Barter Island increases by 65 % after the correction and by 13 % at Komakuk. The difference between the two stations at the last cumulative point (December 1988) is 440 mm for Pm, and 380 mm for Pc. This shift represents 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 shows more cumulative precipitation at the end of the period (3348 vs. 2144 mm for Komakuk). Although the relationship is more homogeneous between these stations, there is a break in the records around 1000 mm for Komakuk, maybe associated with changes in instruments or sensors. Both stations have increases in total cumulative P by 3 %, i.e. a change in precipitation difference from 1204 to 1352 mm between Shingle and Komakuk over the study period (2006–2013).

The central stations show a greater amount of Pm in Dawson (2202 mm) than in Eagle (2027 mm) over the study period. Bias corrections change the total P by 7 and 3 % for Eagle and Dawson, respectively, resulting in a shift in the DMC (Fig. 11c),

TCD
9, 3709–3739, 2015

particularly for the last period of time, to 2265 mm in Dawson and to 2173 mm in Eagle. This shift also represents a slightly smaller precipitation difference between Eagle and Dawson. In the 8 years, the cumulative difference goes from 175 to 92 mm over the study period.

In summary, the DMC for measured and corrected precipitation show that the main change is due to the difference in their corrections (Fig. 11); the north stations show a greater change compared with the central group. The Pc shows in all the cases a smaller precipitation difference between the two countries. This smaller difference leads to a decrease in the P gradient across the border. This result implies that existing precipitation climate maps and information derived from gauge measurement without bias corrections may over-estimate the P 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 the station pairs across US-Canada border. The monthly 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. The corrections for gauge undercatch increase the snowfall by 135 % in January for the Barter Island station. For the Yukon stations, the increase is about 34 % in January. These represent an annual mean loss of 93 mm (100 %) in snowfall and 25 mm (30 %) mm of rain at Barter, while at Shingle Point and Komakuk Beach the corrections are, on average, about 31 mm for snow and 7.5 mm for rain. For Eagle and Dawson stations in the central region, the bias corrections are small. The annual corrections range from 3–16 % for snow, to 3–7 % for rain, much smaller than those for the northern region.

On the annual scale, the Barter Island station in AK shows a yearly mean correction around 65 %, five times greater than the correction at Shingle Point and Komakuk

TCD
9, 3709–3739, 2015

Beach (12 and 14 %) in Canada. In the central region, Eagle station shows an increase by 7 %, meanwhile for Dawson the increase is 3 %. Thus, the bias correction is twice for Alaska compared to the Yukon stations. Relative to the northern region, these corrections are small mainly due to warm temperatures and low 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 *P* 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 the Komakuk Beach-Shingle Point and Eagle-Dawson, do not show any appreciable change as the result of the bias corrections. There is a stronger *P* 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 a greater *P* variability across the regions.

The double mass curve analyses demonstrate a significant change in the *P* 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, alters the *P* difference, resulting in a smaller and inverted precipitation gradient across the border in the northern region. It is very clear from this study that the significant inconsistency exists in the precipitation measurements across the border. This inconsistency is much greater for snowfall than for rain, as gauge snowfall observation has large errors in the windy and cold conditions. This discrepancy should be taken into account when using the *P* data across the national borders for regional climate and hydrology investigations.

The double mass curve (DMC) is a useful tool to evaluate the consistency of observation records over space and time (Searcy and Hardison Clayton, 1960). Some typical issues of observations that DMC can identify include changes in the station locations, and instruments or sensors. Although in this work the DMC has not been

TCD
9, 3709–3739, 2015

constructed against a reference station, the results clearly show some breaks on the slope and gaps in the curves, indicating changes in P 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 P regime. Metadata and information for the stations/networks are necessary to understand the changes in P observations and to improve the homogenization of the precipitation records over the high latitudes.

Classification of P 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 US CRN with the CO-OP station network precipitation measurements, averaged the USCRN hourly temperatures data during P periods into an event mean and used it to group P events into warm (mean temperature $> 5\,^{\circ}$C), near-freezing (mean temperature between 0 and $5\,^{\circ}$C), and freezing (mean temperature $< 0\,^{\circ}$C) conditions. Yang et al. (2005) used the daily mean air temperature to estimate precipitation types (snow, mixed, and rain) when this information is not available for the northern regions. In this study, monthly mean temperatures have been used to determine the warm season (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 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 P dataset developed by Yang et al. (2005) has been used for this analysis. The corrections have been done systematically on a daily time scale that affects the daily P time series. This analysis focuses on the results of monthly and yearly P data and quantifies the changes in P pattern across the AK–YK border. Careful analyses of available daily measured and corrected P data are necessary, since in the northern regions with low P in winter, the bias corrections can easily increase the daily P by a factor of up to 4–5 (Yang et al., 1998, 2005; Benning

TCD
9, 3709–3739, 2015

and Yang, 2005). This means that extreme P 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 important knowledge gap, our efforts are underway to examine the daily corrections, particularly on the heavy and windy P days, and to document the possible underestimation of P extremes over the large northern regions.

Finally, automation of the meteorological observation networks and instruments has been a trend over the past several decades around the world, including both the 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 the US Climate Reference Network (USCRN) and the Surface Weather and Climate Network (SWCN) in Canada. This may reduce the inconsistency in P measurements across US and Canada borders, although the double and single Alter wind shields have been installed with the Geonor gauges in US and Canada, respectively. It is however important to emphasize that automatic gauges also significantly under catch snowfall (Wolff et al., 2015) and the bias corrections are necessary in order to obtain reliable P 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 P data quality and regional climate analyses, including the border regions between the US and Canada.

Acknowledgements. the authors gratefully acknowledge the support from the Global Institute of Water Security at University of Saskatchewan and Environment Canada.

References

Benning, J. and Yang, D.: Adjustment of daily precipitation data at Barrow and Nome Alaska for 1995–2001, Arct. Antarct. Alp. Res., 37, 276–283, doi:10.1657/1523-0430(2005)037[0276:AODPDA]2.0.CO;2, 2005.

Goodison, B. E.: Compatibility of Canadian snowfall and snow cover data, Water Resour. Res., 17, 893, doi:10.1029/WR017i004p00893, 1981.

Goodison, B. E., Louie, P. Y. T., and Yang, D.: Report No. 67, WMO Solid Precipitation Measurement Intercomparison, 1998.

Groisman, P. Y. and Easterling, D. R.: Variability and trends of total precipitation and snowfall over the United States and Canada, J. Climate, 7, 184–205, doi:10.1175/1520-0442(1994)007<0184:VATOTP>2.0.CO;2, 1994.

Leeper, R. D., Rennie, J., and Palecki, M. A.: Observational perspectives from U.S. Climate Reference Network (USCRN) and Cooperative Observer Program (COOP) network: temperature and precipitation comparison, J. Atmos. Ocean. Tech., 32, 703–721, 2015.

Mekis, É. and Vincent, L. A.: An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada, Atmos. Ocean, 49, 163–177, doi:10.1080/07055900.2011.583910, 2011.

Metcalfe, J. R. and Goodison, B. E.: Correction of Canadian winter precipitation data, in: Proc. Eighth Symp. on Meteorological Observations and Instrumentation, Amer. Meteor. Soc. Anaheim, CA, 338–343, 1993.

Nitu, R. and Wong, K.: CIMO Survey on National Summaries of Methods and Instruments Related to Solid Precipitation Measurement at Automatic Weather Stations-Preliminary, available at: http://www.moc.cma.gov.cn/mocdoc/2008/TECH-2008/2(13)_Nitu_Canada.doc, last access: July 2015, 2010.

Nitu, R., Rasmussen, R., Baker, B., Lanzinger, E., Joe, P., Yang, D., Smith, C., Roulet, Y. A., Goodison, B., Liang, H., Sabatini, F., Kochendorfer, J., Wolff, M., Hendrikx, J., Vuerich, E., Lanza, L., Aulamo, O., and Vuglinsky, V.: WMO intercomparison of instruments and methods for the measurement of solid precipitation and snow on the ground: organization of the formal experiment, IOM No. 109, TECO-2012, WMO, Brussels, Belgium, 16–18 October 2012.

Rasmussen, R., Baker, B., Kochendorfer, J., Meyers, T., Landolt, S., Fischer, A. P., Black, J., Thériault, J. M., Kucera, P., Gochis, D., Smith, C., Nitu, R., Hall, M., Ikeda, K., and Gutmann, E.: How well are we measuring snow? The NOAA/FAA/NCAR winter precipitation test bed, B. Am. Meteorol. Soc., 93, 811–829, doi:10.1175/BAMS-D-11-00052.1, 2012.

Sanderson, M.: Notes and correspondence: a comparison of Canadian and United States standard methods of measuring precipitation, J. Appl. Meteorol., 14, 1197–1199, 1975.

Searcy, J. and Clayton, H.: Double-Mass Curves, United States Department of the Interior, Washington DC, 1960.

Šeparović, L., Alexandru, A., Laprise, R., Martynov, A., Sushama, L., Winger, K., Tete, K., and Valin, M.: Present climate and climate change over North America as simulated by the fifth-generation Canadian regional climate model, Clim. Dynam., 41, 3167–3201, 2013.

Sevruk, B. and Klemm, S.: Types of standard precipitation gauges, in: Proceedings of International Workshop on Precipitation Measurement, WMO/IAHS/ETH, St. Moritz, Switzerland, WMO/IAHS/ETH, vol. 227236, 1989.

Wolff, M. A., Isaksen, K., Petersen-Øverleir, A., Ødemark, K., Reitan, T., and Brækkan, R.: Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study, Hydrol. Earth Syst. Sci., 19, 951–967, doi:10.5194/hess-19-951-2015, 2015.

Yang, D.: Double Fence Intercomparison Reference (DFIR) vs. Bush Gauge for “true” snowfall measurement, J. Hydrol., 509, 94–100, doi:10.1016/j.jhydrol.2013.08.052, 2014.

Yang, D. and Ohata, T.: A bias-corrected siberian regional precipitation climatology, J. Hydrometeorol., 2, 122–139, doi:10.1175/1525-7541(2001)002<0122:ABCSRP>2.0.CO;2, 2001.

Yang, D. and Simonenko, A.: Comparison of winter precipitation measurements by six Tretyakov gauges at the Valdai experimental site, Atmos. Ocean, 52, 39–53, doi:10.1080/07055900.2013.865156, 2013.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Elomaa, E., Gunther, T., Bates, R., Pangburn, T., Hanson, C. L., Emerson, D., Copaciu, V., and Milkovic, J.: Accuracy of tretyakov precipitation gauge: result of wmo intercomparison, Hydrol. Process., 9, 877–895, doi:10.1002/hyp.3360090805, 1995.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Bates, R., Pangburn, T., and Hanson, C. L.: Accuracy of NWS 8″ standard nonrecording precipitation gauge: results and application of WMO intercomparison, J. Atmos. Ocean. Tech., 15, 54–68, 1998a.

Yang, D., Goodison, B. E., Ishida, S., and Benson, C. S.: Adjustment of daily precipitation data at 10 climate stations in Alaska: application of world meteorological organization intercomparison results, Water Resour. Res., 34, 241–256, doi:10.1029/97WR02681, 1998b.

Yang, D., Ishida, S., Goodison, B. E., and Gunther, T.: Bias correction of daily precipitation measurements for Greenland, J. Geophys. Res., 104, 6171, doi:10.1029/1998JD200110, 1999.

Yang, D., Goodison, B., Metcalfe, J., Louie, P., Elomaa, E., Hanson, C., Golubev, V., Gunther, T., Milkovic, J., and Lapin, M.: Compatibility evaluation of national precipitation gage measurements, J. Geophys. Res., 106, 1481, doi:10.1029/2000JD900612, 2001.

Yang, D., Kane, D., Zhang, Z., Legates, D., and Goodison, B.: Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions, Geophys. Res. Lett., 32, L19501, doi:10.1029/2005GL024057, 2005.

Zhao, K., Stadnyk, T., Koenig, K., and Crawford, J.: Better Precipitation Product over the Red River Basin, BSc Thesis, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada, 2010.

Table 1. Station information and climate summary.

ID WMO	Country	Station name	Location			Data period		Measurement device snow	Annual means			
			Lat (N)	Lon. (W)	Alt (m)	Start	End		Precipitation (mm)	Min. temp. (°C)	Max. temp. (°C)	Wind speed ($m s^{-1}$)
700860	US	BARTER IS WSO AP	70.13	−143.63	11	1978	1988	US-8 inch Unshielded	157	−27.1	4.6	4
719690	CA	KOMAKUK BEACH ARPT	69.58	−140.18	7	1978	1988	Nipher	197	−27.5	7.4	4
719680	CA	SHINGLE POINT ARPT	68.95	−137.21	49	1978	1988	Nipher	271	−26.6	10.6	3
701975	US	EAGLE	64.78	−141.16	268	2006	2013	US-8 inch Unshielded	253	−22.7	15.5	1
719660	CA	DAWSON AIRPORT	64.05	−139.13	369	2006	2013	Nipher	275	−25.8	15.9	1

TCD
9, 3709–3739, 2015
Inconsistency in precipitation across AK/YK border
L. Scaff et al.

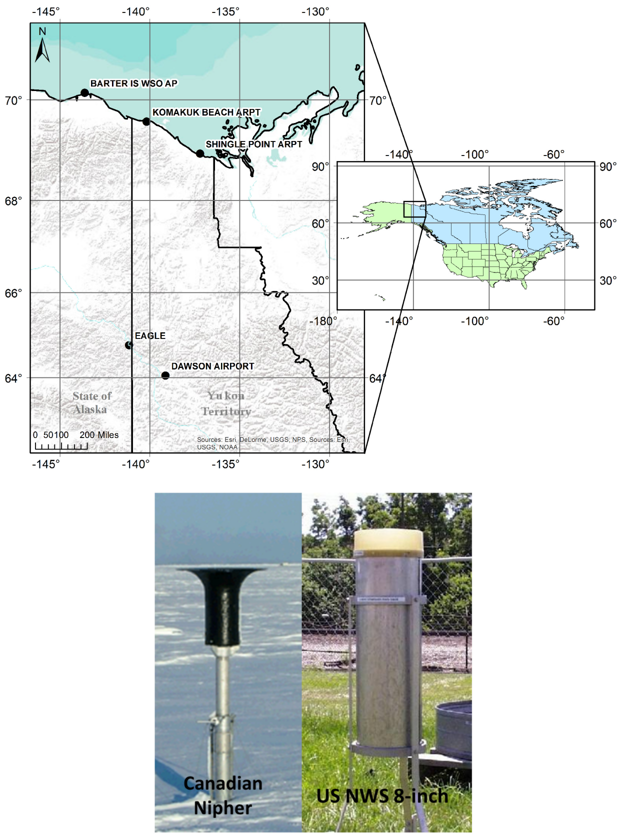

Figure 1. Study areas and locations selected climate stations, and photos of the national standard gauges for USA and Canada.

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

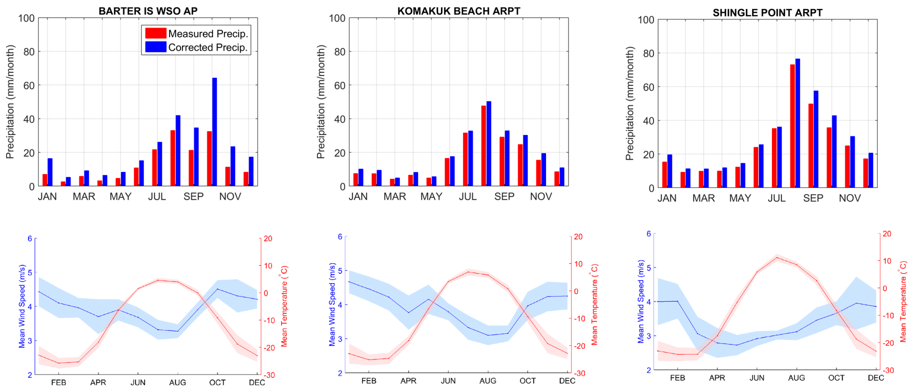

Figure 2. Monthly mean precipitation at 3 stations during 1977–1988 (upper panels) and corresponding monthly mean wind speed and air temperature (bottom panels). Shadows represent the 95 % confidence interval for the temperature and wind speed.

TCD
9, 3709–3739, 2015

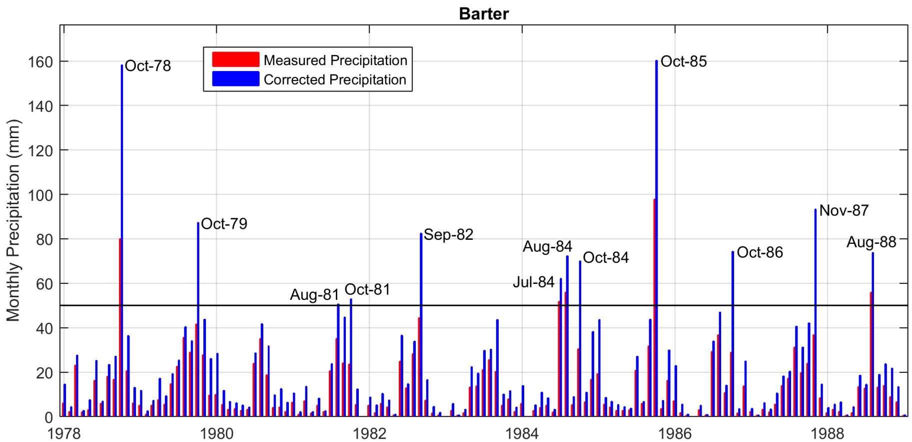

Figure 3. Monthly precipitation records at the Barter station during 1978–1988. The months with more than 50 mm (black line) are labeled.

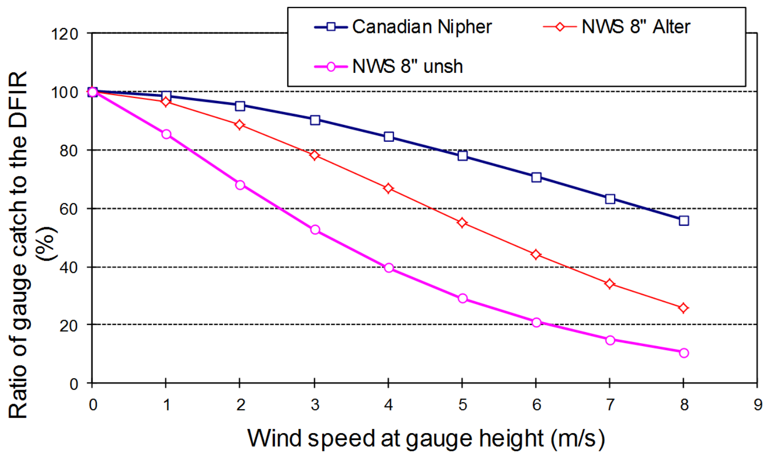

Figure 4. Comparison of the catch ratio of snowfall as a function of wind speed at gauge height for the Alter-shielded or unshielded NWS 8-inc standard gauge and the Canadian Nipher snow gauge. DFIR is the Double Fence Intercomparison Reference (Yang et al., 1998).

TCD
9, 3709–3739, 2015
Inconsistency in precipitation across AK/YK border
L. Scaff et al.

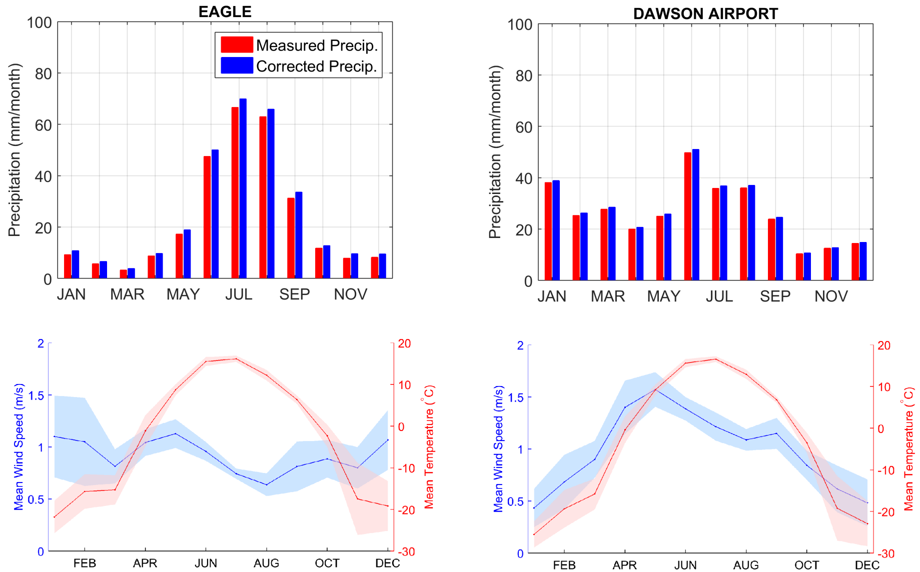

Figure 5. Monthly mean precipitation at 2 stations during 2006–2013 (upper panels) and corresponding monthly mean wind speed and air temperature (bottom panels). Shadows represent the 95 % confidence interval for the temperature and wind speed.

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

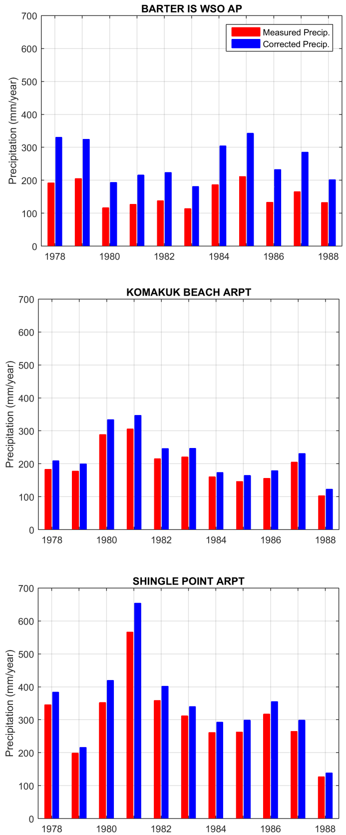

Figure 6. Annual precipitations during 1978–1988 for the 3 stations in the northern group across the border.

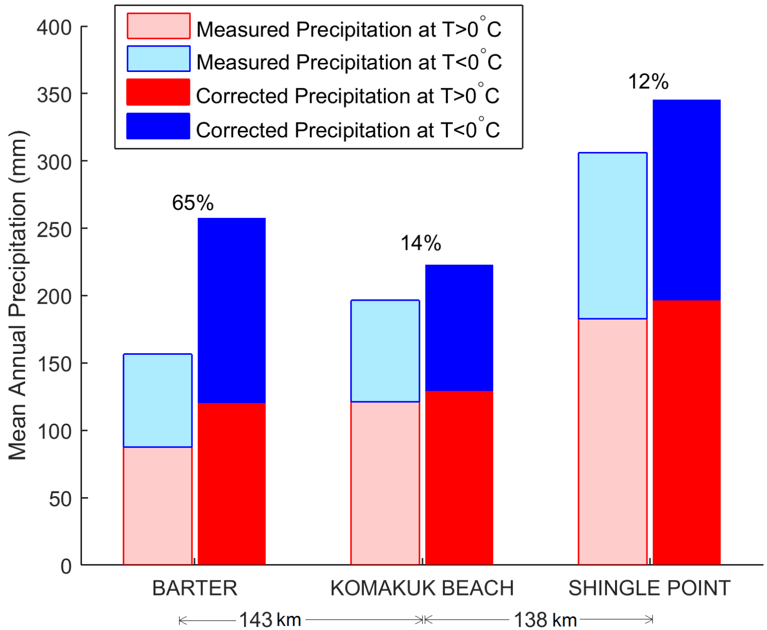

Figure 7. Mean annual (1978–1988) measured and corrected precipitation for cold ($T < 0\,^{\circ}$C) and warm ($T > 0\,^{\circ}$C) months. The percentages are the changes from measured to corrected precipitation.

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

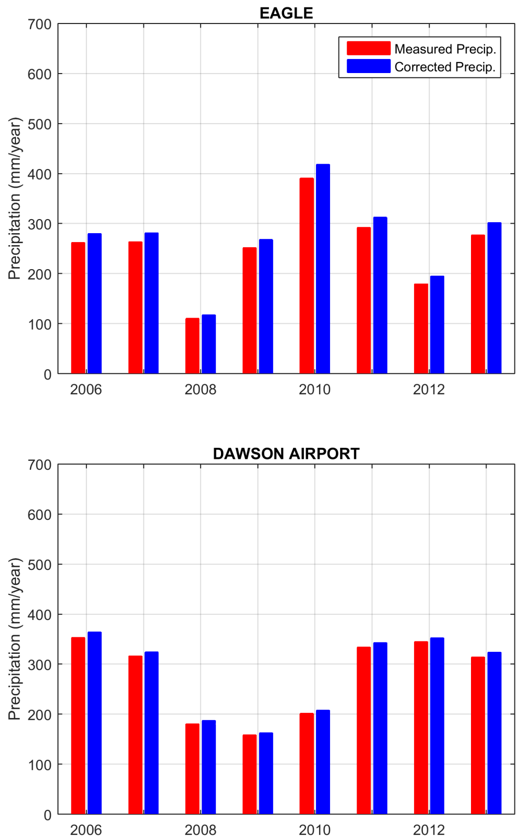

Figure 8. Annual precipitations during 2006–2013 for two stations in the central part of the AK/YK border.

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

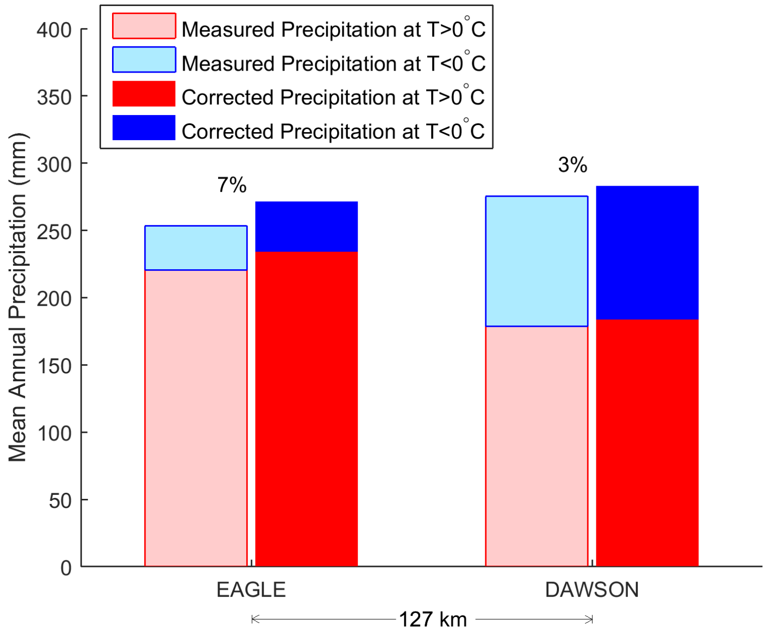

Figure 9. Mean annual (2006–2013) measured and corrected precipitation for cold ($T < 0\,^{\circ}$C) and warm ($T > 0\,^{\circ}$C) months. The percentages are the change from measured to corrected precipitation.

TCD
9, 3709–3739, 2015

Inconsistency in precipitation across AK/YK border

L. Scaff et al.

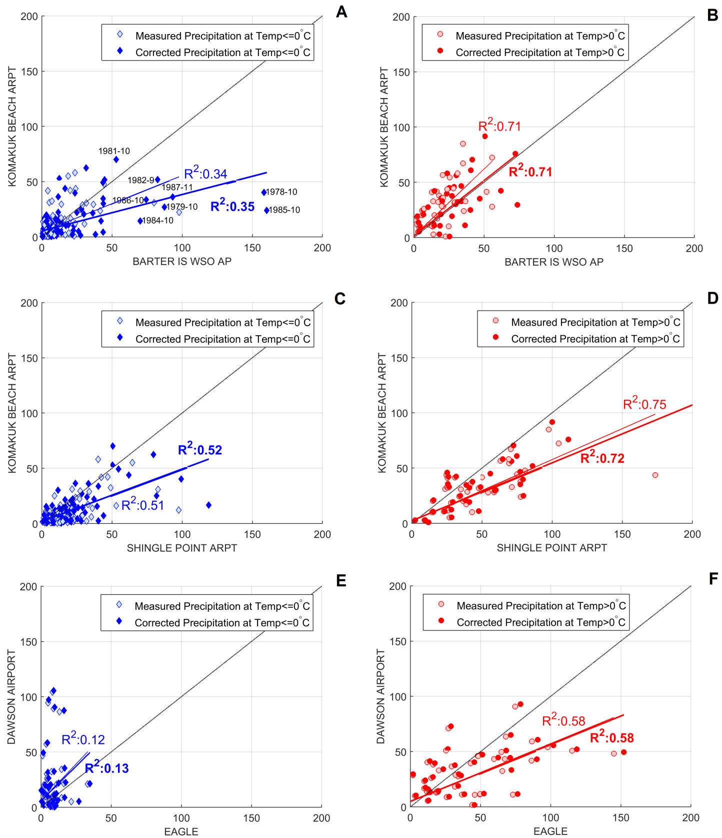

Figure 10. Scatter plots between station pairs for the measured and corrected precipitation. The red color shows warm months and the blue represents the cold months. **(a, b)** Barter and Komakuk comparison across the border, the highest corrected values for Barter (AK) are labeled with the date to compare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

TCD
9, 3709–3739, 2015

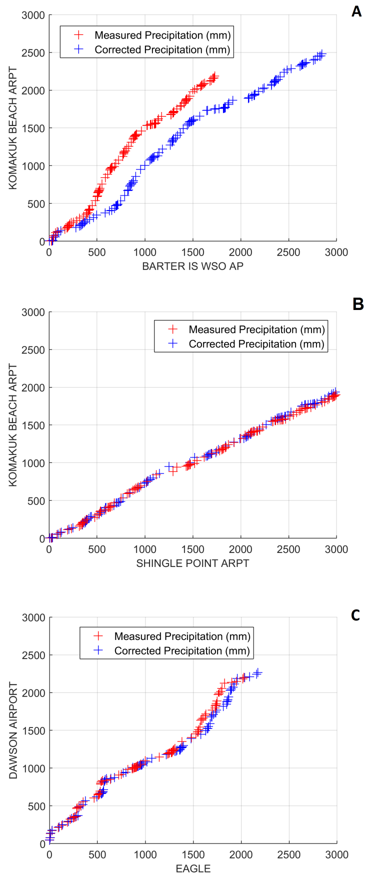

Figure 11. Double mass curves between station pairs. The red color shows the warm months and blue represents the cold months. The top and the central plots compare the stations for the northern group and the bottom one is the central station comparison across the border.