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The Environment and Climate Change Canada solid precipitation intercomparison data from Bratt's Lake and Caribou Creek, Saskatchewan

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Abstract. Prior to the beginning of the World Meteorological Organization's (WMO) Solid Precipitation Inter-Comparison Experiment (SPICE, 2013-2015), two precipitation measurement intercomparison sites were established in Saskatchewan. Caribou Creek, located in the southern Boreal forest, and Bratt's Lake, located in the southern plains, were meant to be a contribution to the international SPICE project but also to examine national and regional issues in measuring solid precipitation. It is also fortunate that the Changing Cold Regions Network (CCRN) Special Observation and Analysis Period (SOAP) occurred from 2014 to 2015, overlapping with the SPICE intercomparison period. Following SPICE, the two Saskatchewan sites continued to collect core meteorological data (temperature, humidity, wind speed, etc.) as well as precipitation observations via several automated gauge configurations, including the WMO automated reference and the Meteorological Service of Canada's (MSC) network gauges. In addition, manual snow surveys to collect snow cover depth, density, and water equivalent were completed over the duration of the winter periods at the northern Caribou Creek site. Starting in the fall of 2013, the core intercomparison precipitation and ancillary data continued to be collected through the winter of 2017. Automated observations were obtained at a temporal resolution of 1 minute, subjected to a rigorous quality control process, and aggregated to a resolution of 30 minutes. The manual snow surveys at Caribou Creek were generally performed every second week during the SPICE field program and reduced to monthly following SPICE. The Saskatchewan SPICE data are available at https://doi.org/10.18164/63773b5b-5529-4b1e-9150-10acb84d59f0. The data collected at the Saskatchewan SPICE sites will continue to be useful for transfer function testing, Numerical Weather Prediction and hydrological forecasting verification, ground truth for remote sensing applications, as well as providing reference precipitation measurements for other concurrent research applications in the cold regions.

1 Introduction

Cold region hydrology and climatology research and monitoring requires accurate measurements of solid precipitation, crucial for water resource forecasting, driving climate and hydrological models, and climate monitoring and trend analysis (Barnett et al., 2005; Gray et al., 2001; Bartlett et al., 2006; Laukkanen, 2004). The systematic bias issues in the measurement of snowfall, either via a manual observer or automated measurements, are well documented (e.g. Sevruk et al., 1991; Goodison et al., 1998) and have resulted in international intercomparison initiatives such as the World Meteorological Organization's (WMO) Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) and the Solid Precipitation Inter-Comparison Experiment (SPICE; Rasmussen et al., 2012; Nitu et al., 2012). The objectives of these intercomparisons were to examine the relative systematic biases of a variety of instrument configurations and to provide solutions for adjusting and homogenizing solid precipitation data such as in Yang et al. (1998, 2005), Sevruk et al. (2009), Wolff et al. (2015) and Kochendorfer et al. (2016, 2017a, 2017b, 2018).

During SPICE, there were eight sites that operated at least one Double Fence Automated Reference (DFAR), including Caribou Creek and Bratt's Lake (Nitu et al., 2012). The DFAR configuration consists of the same large octagonal double wind fence used by the WMO Double Fence Intercomparison Reference (DFIR; Yang et al., 1993, Goodison et al., 1998) only with the DFIR manual Tretyakov precipitation gauge replaced with either a Geonor T-200B or an OTT Pluvio^2 automatic precipitation gauge (Fig. 1). The relative performance of the DFIR can be traced back to the intercomparison between the DFIR and a bush shielded gauge at the Valdai, Russia research station (Yang et al., 1993) where the DFIR was shown to have a catch efficiency of 94%, 92% and 90% for rain, mixed, and snow respectively as compared to the bush gauge. Yang (2014) further refined this intercomparison by adding more data and showed that the catch efficiency of the DFIR was 3% to 6% higher than previously shown. In turn, the performance of the DFAR can be related to the DFIR from historical comparisons (Smith, 2009) and comparisons during SPICE (Nitu & Roulet, 2016). Smith (2009) showed that the catch of the DFAR for dry snow (snowfall at air temperatures < -2° C) was approximately 86% of the total of the adjusted DFIR (using the Yang et al. 1993 adjustment), and approximately 93% of the unadjusted DFIR catch. Nitu & Roulet (2016) showed that intercomparisons between the DFIR and DFAR during SPICE yielded a DFAR catch efficiency of approximately 92%.

Another requirement of SPICE for sites operating a DFAR reference was the inclusion of an Alter shielded and unshielded gauge pair, either Geonor T-200B or OTT Pluvio^2. For SPICE, the intent was to broaden the intercomparisons amongst sites that were not able to install and operate a DFAR but had the capabilities to operate the Alter shielded and unshielded pair of gauges. The shielded and unshielded pair of Geonor T-200B gauges operated at Bratt's Lake is shown in Fig. 2.

One of the legacies of the WMO-SPICE project is the high quality precipitation and ancillary data set consisting of multiple precipitation gauge configurations (different gauge models with various measurement principles utilizing many wind shield designs), wind speed measurements at both gauge height and the standard 10 m height, temperature, and often precipitation type observations (via optical sensors). The bulk of the international WMO-SPICE data set will be made available by the WMO once data agreements have been completed. In parallel to data collection, SPICE also developed robust data quality control techniques that can be applied to both SPICE and post-SPICE data (Kochendorfer et al., 2017b).

The SPICE precipitation data, besides being useful for intercomparing gauge configurations for performance assessment and data homogenization, represents a high quality precipitation data set, useful for remote sensing validation, hydrological modelling applications, and further refinement and testing of precipitation gauge transfer

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functions. Data collected in western Canada at the Saskatchewan SPICE sites represents a contribution to the Changing Cold Regions Network (CCRN; DeBeer et al., 2016) and more specifically for the CCRN Special Operations and Analysis Period (SOAP) which was conducted from October 1, 2014 to September 30, 2015 across all of the CCRN "Water, Ecosystem, Cryosphere and Climate (WECC)" observatories, including the Saskatchewan WMO-SPICE sites.

2 Sites, methods, and instrumentation

Table 1 shows the location and climate details of both Bratt's Lake (XBK) and Caribou Creek (CCR). The locations of the sites are indicated on the map in Figure 3.

2.1 Caribou Creek

The Caribou Creek SPICE site was established in November of 2012 and was fully operational by February 2013. The site is located in the southern Boreal Forest, about 100 km northeast of Prince Albert, Saskatchewan. Harvested in 2004 and previously instrumented as part of the Boreal Ecosystem Research and Monitoring Site project (BERMS; Barr et al., 2012) and the FluxNet Canada program (Margolis et al., 2006), the site consists of a regenerating Jack Pine canopy with tree heights averaging about 2 to 3 m. This makes the site opportunistic for measuring precipitation in a bush sheltered area, similar to, but not exactly the same as, the Valdai site (Yang et al., 1993) where unsheltered gauges were compared with gauges located in the bush. The pre-existing Geonor T-200B (used for BERMS) was nearly ideally located within the well sheltered bush area and would become the site "Bush" gauge (Fig. 4a). Prior to the beginning of the SPICE intercomparison period, a clearing with dimensions of approximately 60 m x 40 m was created about 100 m from the bush gauge and a DFAR was constructed inside the clearing (Fig. 4b). Along with some other instrumentation tested for SPICE, the clearing also hosted the Alter shielded (Fig. 4c) and unshielded (not shown) Geonor T-200B.

Wind speed at CCR and reported here was measured at 2 m above the ground in the clearing using a Gill cup wheel anemometer. Although not reported here, wind speed was also measured at 3 m height in the centre of the clearing and at 2 m height near the bush shielded Geonor gauge (Figure 4a). Temperature and relative humidity (not reported) were measured with a Campbell Scientific HMP45C mounted at 1.5 m above the ground inside a naturally aspirated radiation shield installed near the centre of the clearing.

During SPICE, CCR hosted an automated SWE sensor, and to facilitate testing and intercomparison of this sensor, manual snow surveys to measure site SWE were performed every two weeks throughout the SPICE campaign (Smith et al., 2017). Following SPICE, the manual snow surveys continued to be performed monthly (with the exception of the winter of 2015/2016 which had no snow surveys). The snow survey used a double sampling technique (Rovansek et al., 1993) in which 5 bulk density samples were taken using an ESC-30 snow tube sampler (Farnes et al., 1983) with a total of 50 snow depth measurements taken with a snow rod between the density samples. The snow survey transect started in the vegetated area south of the clearing, crossing the clearing into the vegetated area to the north.

2.2 Bratt's Lake

The Bratt's Lake observatory is located approximately 30 km southwest of Regina, Saskatchewan. The site is situated on the open prairie with very little topographic relief, resulting in high exposure and therefore relatively high wind speeds (Table 1). The lack of vegetation other than short grasses enhances the exposure. The precipitation infrastructure was initially installed in 2003 and included a DFIR as the manual reference for the DFAR as well as other automatic gauges including the Alter shielded Geonor T-200B (Smith, 2009). Prior to SPICE, the site was fully automated, including the two DFARs (Figure 1 right) and the same Alter shielded and unshielded Geonor T-200B precipitation gauges (Fig. 2) as at CCR. Wind speed was measured by am R.M. Young propeller anemometer at a height of approximately 2 m above the ground. Temperature and relative humidity (not reported) were measured with a Campbell Scientific HMP45C instrument inside an aspirated Stevenson screen at 1.5 m above the ground. Unlike CCR, there were no manual snow surveys performed at XBK.

2.3 Precipitation gauge heating

Prior to the start of the SPICE field campaigns, the organizing committee decided that the reference precipitation gauges used for SPICE needed to have rim heaters to prevent gauge capping (where the gauge orifice is blocked or partially blocked with snow). For the Geonor gauges discussed here, the heaters and thermistors for monitoring and switching were added prior to installation in the field. The heaters are best illustrated in Fig. 2 (right) where the external "chimney" is wrapped with a heating element (seen as yellow in the photo). The heating tape extends down into the lower "chimney" which is not visible in the photo, thus preventing melted snow from refreezing in the lower chimney before reaching the storage bucket inside the gauge. The heaters were turned on when the air temperature dropped below 2 °C and were controlled by thermistors embedded in the gauge rim such that the rim temperature did not exceed 2 °C. There were no lower temperature limits to the heater switching, but it was observed that the heaters could not maintain the rim temperatures at 2 °C when the air temperature was below -5 °C, although generally kept the rim temperature above the ambient air temperature.

2.4 Precipitation gauge "charging"

To prevent freezing of the precipitation gauge bucket contents over the winter, the gauges were "charged" with 3 to 4 L of an antifreeze mixture consisting of 60% methanol and 40% propylene glycol. The methanol serves to decrease the density of the antifreeze mixture so that the contents do not stratify and freeze. A light weight electrical insulating oil (approximately 0.5 L) was then poured on top of the bucket contents to prevent evaporation of both the antifreeze and the collected precipitation.

3 Data collection, quality control, and post-processing

3.1 Data collection

Since both the XBK and CCR sites were required to be consistent with the other international SPICE sites, the data collection frequency for the automated data was standardized. The data loggers performed a program execution and instrument read every 20 seconds and these data were averaged and output once per minute. The 1 minute data were stored on the site data loggers and retrieved daily by the site computer. Typically once per week, the site computers were accessed remotely and the data retrieved for quality control and post-processing.

3.2 Quality assurance and control

Following retrieval, the 1 minute data were filed into time consistent (i.e. no gaps in the time series even if the data are missing) monthly files. The data were graphed and the time series examined for instrument failures and inconsistencies. The same quality control process applied to the international SPICE data (i.e. Kochendorfer et al., 2017b) was used for our data on both the SPICE and post-SPICE observation periods. This is an automated process which removes out-of-range outliers and unrealistic data jumps, the thresholds for which are set using realistic limits for each site. For the precipitation gauge bucket weight data, this also includes the removal of data jumps related to gauge servicing (bucket emptying and/or charging). Anything missed or flagged by the automated quality control process is then examined and managed manually.

Quality control of the snow survey data was largely completed at the time of digitization when the field observation sheets were transferred into a spreadsheet. Snow depth data were plotted and examined for outliers, which were generally from misreading the snow rod or incorrectly transcribing the observation in the field. Outliers were removed and not included in the site mean or standard deviation. The same was done for the density samples.

3.3 Precipitation post-processing

The quality controlled 1 minute bucket weight data from the precipitation gauges are first smoothed using a Gaussian filter with a 4 minute running window. This filter smooths any spikes in the time series resulting from mechanical or electrical noise. The time series is then zeroed to the start of the season and further filtered using the Brute Force precipitation filter (Pan et al., 2016) which cleans the remaining noise out of the time series and provides a first guess at determining precipitation. As described by Pan et al. (2016), this algorithm iteratively balances the positive and negative noise in the time series and results in precipitation when the positive increase in bucket weight exceeds the noise by a user defined threshold (set at 0.05 mm for this 1 minute data set). However, the Brute Force filter, from this point on referred to as the Brute Force Unsupervised (BFU) filter, balances the noise by forcing the total precipitation in the time series to equal the final precipitation gauge bucket weight accumulation, making the assumption that the longer term increase in bucket weight in the accumulating gauge is an accurate depiction of total precipitation in the time series. However, as indicated by Pan et al. as referenced above, systematic negative changes in the bucket weight, which are usually caused by evaporation of the bucket contents, causes this assumption to fail. For this reason, manual intervention is required to adjust the filter's baseline such that

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evaporation errors are negated. This process is called Brute Force Supervised (BFS) and effectively adds precipitation to the time series that BFU misses due to evaporation. The resulting time series is then re-sampled to produce 30 minute precipitation estimates.

3.4 Missing meteorological and precipitation data

The missing data flag in the SK SPICE dataset is "-999" and is present when the instrument malfunctions, the data failed to collect (e.g. logger or power outage), or was removed during the quality control process. No gap filling of the meteorological data was performed. During data outages, the precipitation gauges continue to accumulate precipitation whether or not the data are recorded, and thereby preserve the accumulated precipitation measurement during the outage. This precipitation amount, although can't be distributed during the outage, is kept in the archive at the end of the missing period. Data in the record, regardless of the source, are flagged with a "1" in the Flag column to indicate that more than one third of the 1 minute values are missing from the aggregation. In the case of precipitation, if the 30 minute reported value represents a period longer than 30 minutes, the Flag column is also "1" and the period length can be determined by counting the number of previously missing 30 minute periods.

3.5 Wind undercatch

The precipitation data published here are not adjusted for wind undercatch. However, this data set includes all of the ancillary data required to perform adjustments using various published techniques and transfer functions (i.e. Wolff et al., 2015, Kochendorfer et al., 2017b, Smith, 2009). The data flags are included to assist the user in making an adjustment for wind. It is strongly suggested that precipitation data with a Flag=1 (see above) not be adjusted as the wind and temperature conditions during the actual precipitation event are unknown.

4 Precipitation summaries

Table 2 shows the seasonal accumulations of precipitation for both Bratt's Lake and Caribou Creek and for the various gauge configurations. Note that the seasonal totals are for 1 October through 30 April, unless noted otherwise. Several seasonal accumulations are abbreviated due to data availability beginning later in the year. These are indicated with an (I) in the table and the beginning of the accumulation period is noted in the footnote under the table. The corresponding accumulated precipitation time series are shown in Fig. 5. Figure 6 shows the Caribou Creek SWE measurements, calculated as the product of the mean transect snow depth (n=50) and the mean transect density (n=5), shown in units of mm of water equivalent (w.e.).

5 Applications

The precipitation data collected at the Bratt's Lake and Caribou Creek sites during the SPICE intercomparison period (2013/2014 and 2014/2015) were a contribution to the WMO-SPICE intercomparison and used to develop the SPICE transfer functions (Kochendorfer et al., 2017b, 2018). The snow survey data over the same period were used as the reference for assessing the performance of an automated SWE sensor (Smith et al., 2017). With the continuation of the data collection at these sites, the 2015/2016 and 2016/2017 (and beyond) data are used for an

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independent assessment of the SPICE transfer functions, providing data from both the reference gauge configuration (DFAR) and a test gauge configuration (Geonor SA). Figure 7, as an example, shows the unadjusted (solid black) and adjusted Geonor SA (solid red and blue; using the SPICE Eq. 3 and Eq. 4 transfer functions from Kochendorfer et al., 2017b) accumulated time series of precipitation at Caribou Creek (Fig. 7a) and Bratt's Lake (Fig. 7b) for the 2016/2017 winter as compared to the accumulated DFAR (dashed black) for the same period. Preliminary results from Caribou Creek (Fig. 7a) suggest that both of the SPICE transfer functions (Eq. 3 which incorporates air temperature and Eq. 4 which does not) over-adjust the winter precipitation at this site by approximately 8%. Alternatively, the preliminary results from Bratt's Lake (Fig. 7b) suggest that both transfer functions under-adjust the winter precipitation at this site by nearly 30%.

Within the CCRN program, Pan et al. (2016) recently carried out precipitation bias adjustments at several research sites in the CCRN domain, however Bratt's Lake and Caribou Creek were not included. That analysis used a transfer function derived from a single test site to adjust precipitation measured in the much wider network of CCRN stations, resulting in an unknown uncertainty in the application. The application of the SPICE transfer functions is also not without uncertainty (as shown in Fig. 7) but one would expect that transfer functions based on multiple sites and combined data should be more widely applicable and therefore used for future precipitation data adjustments in cold regions. This Saskatchewan SPICE and post-SPICE data set has, and will continue to be a valuable asset for both testing and refining precipitation adjustment methodologies.

6 Data Availability

The Saskatchewan SPICE data from the winters of 2013/2014 through 2016/2017 can be found on the Government of Canada Open Data portal at: https://doi.org/10.18164/63773b5b-5529-4b1e-9150-10acb84d59f0. This includes the 30 minute precipitation and ancillary data (temperature and wind speed) from both Caribou Creek and Bratt's Lake and the bi-weekly or monthly snow survey summaries from Caribou Creek. The metadata, also found at the above link, describes the data format and summarizes the information in this manuscript. It can be downloaded in both French and English.

7 Summary

The Bratt's Lake and Caribou Creek Saskatchewan SPICE data collected by ECCC during the winters (October through April) of 2013/2014 to 2016/2017 includes the WMO DFAR as a solid precipitation reference measurement, the single Alter Geonor T-200B (which is the configuration most commonly used in the MSC climate network), a bush shielded Geonor T-200B (at CCR only as a proxy for a bush measurement as at Valdai, Russia), wind speed at gauge height, and air temperature. Although these data do not represent all of the data collected during and after WMO-SPICE at CCR and XBK, they do include the core precipitation and ancillary measurements. Available on the Government of Canada Open Data Portal, these data have been, and will continue to be used for instrument intercomparisons and validation of precipitation gauge transfer functions. It will be a useful data set for

NWP and Hydrological model validation and remote sensing ground truthing, with the intercomparison sites and infrastructure available for future in-situ intercomparison projects.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

This article is part of the special issue "Water, ecosystem, cryosphere, and climate data from the interior of Western Canada and other cold regions". It is not associated with a conference.

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Table 1: Saskatchewan SPICE site locations (Latitude, Longitude, and Elevation), mean annual air temperature (T_{air}), mean annual total precipitation (P), and mean wind speed at gauge height (U_{gh}).

Site (Abbreviation)	Lat.	Lon.	Elev.	Mean T_{air}*	Mean P*	Mean U_{gh}**
Bratt's Lake (XBK)	50.200°	-104.711°	585 m	3.1 °C	389.7 mm	4.4 m s^{-1}
Caribou Creek (CCR)	53.945°	-104.649°	519 m	0.9 °C	427.3 mm	2.6 m s^{-1}

*From the 1981-2010 Environment Canada Climate Normals at the nearest long term climate station (Regina Airport for Bratt's Lake and Nipawin Airport for Caribou Creek)

**Mean for the 2013-2015 SPICE period at the site, approx. 2 m above the ground

Table 2: Seasonal totals of precipitation (October through April, where available). Incomplete seasonal totals (I) are usually due to precipitation data starting later than October 1 (see footnotes).

	XBK		CCR		
Year	DFAR(mm)	Geonor SA(mm)	DFAR(mm)	Geonor Bush(mm)	Geonor SA(mm)
2013/2014	170.2	100.7	279.6	259.0	224.1
2014/2015	141.3(I^1)	78.4(I^1)	106.3(I^2)	172.6	86.8 (I^2)
2015/2016	48.1(I^3)	33.2(I^3)	189.3	174.3	No data
2016/2017	168.8	104.4	310.3	301.9	134.4(I^4)

[1]begins 11 Oct 2014; [2]begins 4 Dec 2014; [3]begins 1 Dec 2015; [4]begins 9 Nov 2016

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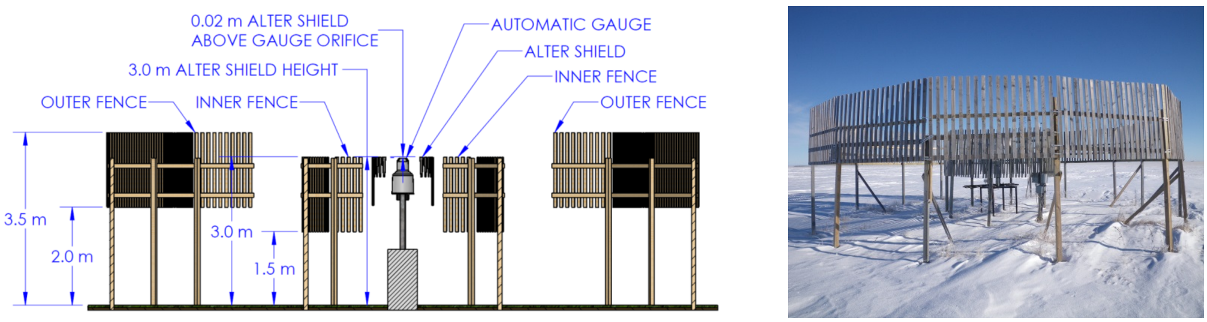

Figure 1: Conceptual diagram (left; Nitu & Roulet, 2016; diagram courtesy of Jeff Hoover, Environment and Climate Change Canada) and photo (right; Bratt's Lake) of the WMO DFAR.

Figure 2: The SPICE Alter shielded (left) and unshielded (right) Geonor T-200B gauge pair at Bratt's Lake.

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Figure 3: Location of the Caribou Creek and Bratt's Lake SK sites in western Canada.

a)  b)  c) 

Figure 4: Precipitation gauge installations at the Caribou Creek SPICE site: a) Bush shielded Geonor T-200B with Alter shield, b) DFAR with Geonor T-200B in clearing and c) Alter shielded Geonor T-200B in clearing.

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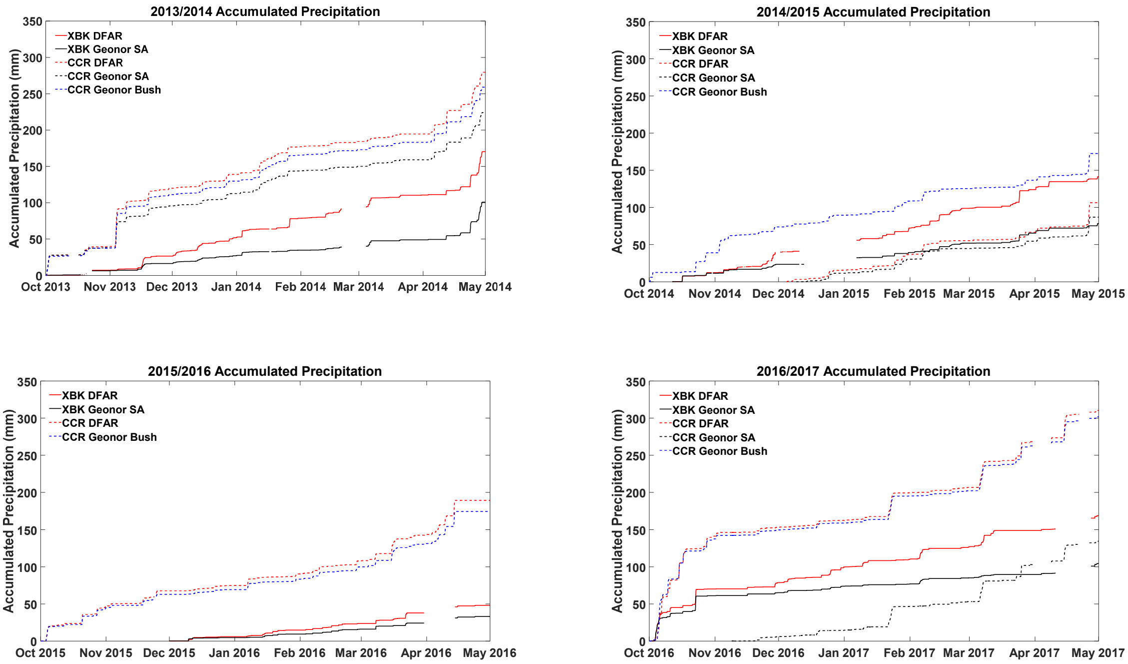

Figure 5: Seasonal time series of accumulated precipitation for the various gauge configurations at Bratt's Lake and Caribou Creek. Note that although the accumulation season is from 1 October through 30 April, not all time series start at the beginning of the season due to gauge or site issues (see Table 2).

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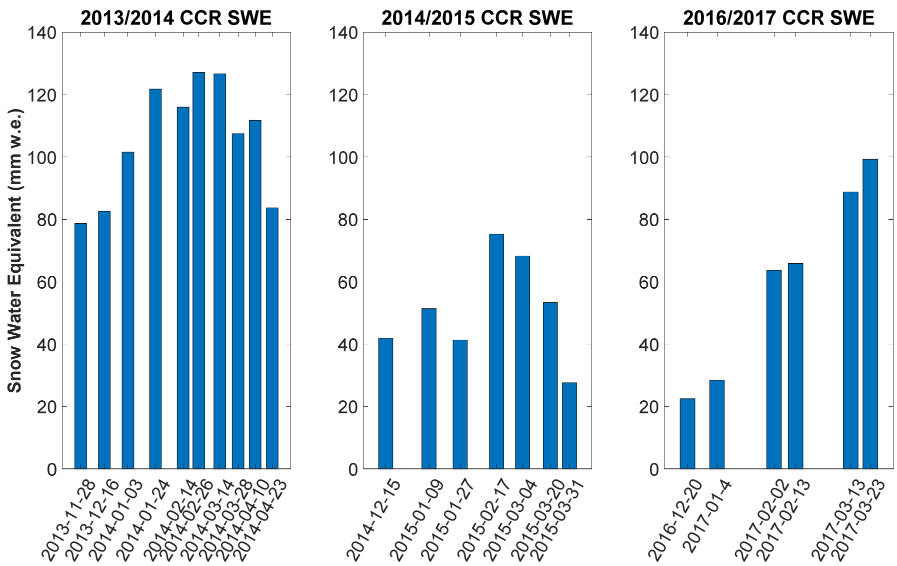

Figure 6: Caribou Creek SWE measurements by date for 2013/2014, 2014/2015, and 2016/2017.

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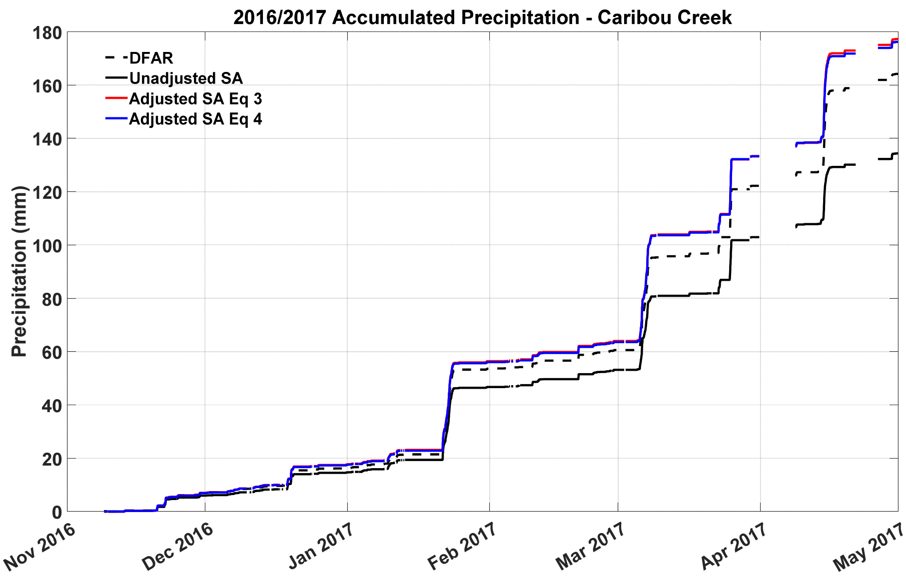
a)



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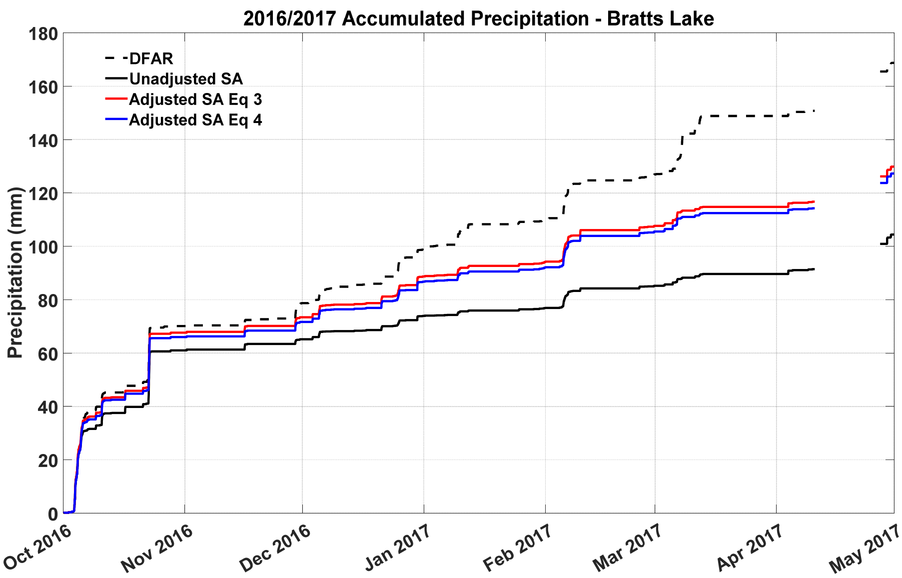

Figure 7: 2016/2017 winter accumulated precipitation time series from a) Caribou Creek and b) Bratt's Lake showing the unadjusted single Alter Geonor T-200B (solid black), the adjusted single Alter Geonor T-200B (read and blue solid; via the SPICE Eq. 3 and Eq. 4 transfer functions from Kochendorfer et al. 2017b), and the DFAR (dashed black).