Automatic Double Fence Reference (DFAR) for measuring solid precipitation: Gauge Based Characterization

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Abstract

Solid precipitation is one of the most complex parameters to be measured. Since the intercomparison on the methods of measurement of solid precipitation organized by the World Meteorological Organization (WMO) from 1989 to 1993 (B Goodison et al., 1998), significant advancements have been made in developing and using operationally automatic instruments. The ability to characterize the measurement performance of these instruments is a priority for the scientific and user community.

The Commission for Instruments and Methods of Observation (CIMO) of the WMO organized between 2010 and 2016 an intercomparison of automated instruments measuring solid precipitation. The Solid Precipitation Intercomparison Experiment (WMO SPICE) took place with field experiments on multiple sites, around the globe, between 2013 and 2015.

The viability of SPICE results depends on the quality and consistency of the field reference systems used on all participating sites. For assessing automatic instruments, field references using automatic instruments were required for SPICE to address the need for high temporal sampling and reporting frequency, down to as low as minutely scales. The Automatic Double Fence Reference (DFAR) for the measurement of solid precipitation was defined and characterized during SPICE, based on the Secondary Reference system recommended at the conclusion of the WMO Solid Precipitation Intercomparison 1989-1993 (Goodison et al, 1998). The DFAR was configured using commonly used weighing type precipitation gauges. Two models with wide operational use were selected; Geonor T200-B3 and OTT Pluvio^2. Each SPICE participating site configured its field reference using one or both of these instruments.

This paper characterizes the relative performance of a field reference system DFAR using
these two gauges, as a function of the operating conditions. These results will allow linking
the results from sites operating DFAR references systems, using either of these two gauges.
The characterization of the DFAR against a Secondary Field Reference, DFIR, as
recommended by (Goodison et al, 1998) is outside the scope of this paper.

1. Introduction

Over the last two decades an increasing percentage of precipitation data used in a variety
of applications have been obtained using a variety of automatic instruments, as many new
and emerging applications (e.g., climate change, nowcasting, water supply, complex terrain,
average warnings, etc) require higher temporal resolution data.

The 2008 CIMO Survey on the instruments used for the measurement of precipitation
(Nitu, Wong, 2010) indicate that a large variety of automatic precipitation gauges and
configurations are currently used for the measurement of solid precipitation, worldwide,
including in the same country, which could create difficulties for the users accessing the
precipitation databases, having major consequences for the measurement accuracy and
consistency of local and global precipitation time series. Because of the non-consistent data
sets, it is difficult to compile local and large-scale climatology of solid precipitation, develop
accurate water budgets, or effectively validate satellite observations.

The Solid Precipitation Intercomparison Experiment (WMO SPICE), organized by the
Commission for Instruments and Methods of Observation (CIMO) of the WMO between
2010 and 2016, focusing on characterizing the performance of measurement of the currently
available automatic instruments measuring precipitation, and specifically, solid precipitation,
through coordinated experiments organized on multiple sites around the globe.
Establishing a consistent, well characterized and feasible field reference system for the
SPICE experiments has been the keystone of the project, as the basis for the compatibility
and reproducibility of results among the participating sites. The measurement of
precipitation cannot be directly traced to absolute references, as it’s not possible to define
the “true” amount of precipitation falling or fallen relative to the amount reaching the
detection system of any given automatic instrument, at any single point.

At its conclusion, the WMO Intercomparison on Solid Precipitation, Goodison et al.
(1998) recommended the secondary field reference for the measurement of solid precipitation,
based on the experience and instrumentation available at that time, known as the DFIR
(Double Fence Intercomparison Reference), and using manual measurement methods. The
DFIR is an “octagonal vertical double-fence inscribed into circles of 12 m and 4 m in
diameter, with the outer fence 3.5 m high and the inner fence 3.0 m high surrounding a
Tretyakov precipitation gauge mounted at a height of 3.0 m. In the outer fence there is a gap
of 2.0 m and in the inner fence of 1.5 m between the ground and the bottom of the fences.”
(see Fig. 1). The SPICE International Organizing Committee (IOC) adopted the octagonal
double fence as defined by Goodison et al (1998), and using automatic gauges as measuring
instruments. The SPICE IOC introduced the term DFIR-fence when referring to the octagonal
double fence, only. The configuration consisting of a DFIR-fence with automatic instruments
at the centre of the octagonal double-fence, surrounded by a single alter shield was labeled
the Double Fence Automatic Reference (DFAR) (see Fig. 1).

A standard SPICE field reference system, type R2 consists of a DFAR, with an automatic
weighing gauge surrounded by a single Alter windshield and a precipitation detector, if
available. The automatic instruments for the DFAR used in SPICE are weighing gauges,
selected for their broad operational use and for the good documentation of their performance, principle similar to that used for the 1989-1993 WMO Intercomparison. As noted in CIMO Guide #8, part 1, Chapter 6, Measurement of Precipitation, “only the weighing type (gauge) is satisfactory for measuring all kinds of precipitation, the use of the tipping bucket type of precipitation gauges being for the most part limited to the measurement of rainfall.”

An automatic weighing gauge weighs the precipitation collected in a large bucket, and calculates the precipitation amounts based on the detected mass or load and the size of its opening. The WMO CIMO Survey of 2008, (Nitu and Wong, 2010) showed that the Geonor T-200B3 gauge (with 3 transducers) and the OTT Pluvio² gauge were the weighing type gauges most widely used operationally, (Fig. 2a) and these were recommended for use in the SPICE reference, R2. Each participating site, configured its R2 reference with the weighing type gauge most widely used in the respective country. An R2 system with a Geonor gauge is labeled as R2G, while a R2 system using a Pluvio² gauge is named R2P.

Based on the practice of several participating countries (e.g. USA) all gauges used as part of the R2 reference are recommended to be heated with the temperature of the rim maintained at 2°C, while the ambient temperature is below 2°C.

### 1.1 SPICE Reference Data Set

To ensure the reliability of the SPICE results and their documented traceability, The SPICE Reference Dataset is, ideally, an unbiased, low variance, noise filtered, artifact-free data set with great sensitivity, demonstrated to be independent of the type of gauge used.

The ability to relate the reference data obtained from a R2G and R2P, respectively, is critical for the interpretation of the SPICE intercomparison results for instruments tested at different locations. This paper focuses on examining the data from the two systems as a function of the
conditions at the sites (temperature, wind, relative humidity, precipitation type), and the precipitation threshold, in an effort to enable the transfer of results among the participating sites and for providing recommendations for the configuration of a reliable field reference system for future applications.

The data from the three sites, equipped with two DFARs, CARE (Canada), Bratt’s Lake (Canada), and Gochang (Rep of Korea) were used for this study.

1.2 Weighing Gauges Characteristics

For the Geonor T200-B3 gauge (Fig. 2b) the bucket content is weighted using a precision load cell with a high-tension vibrating wire (VW) transducer. Under load, the wire vibration frequency is proportional to the weight detected (P), based on a quadratic relation (Geonor T-200B Precipitation Gauge User Manual, Rev. 8 and Bakkehøi et al, 1985). The signal from a transducer is amplified into a measurable quantity read with an external data logger. This signal is converted into a precipitation amount corresponding to the weight of the bucket content, and this is the data used for the analysis presented in this paper. The Geonor gauge used in the R2 system for SPICE uses three identical vibrating wire transducers, equally distanced, supporting a plate with the bucket.

For the Pluvio² weighing gauge, (Fig. 2c) the bucket content is weighted using a high-precision stainless steel load cell, hermetically sealed against environmental influences. Through internal processing (proprietary algorithm), the weight of bucket content is determined every 6 seconds with a resolution of 0.01 mm. Several data products are part of the message output of the Pluvio². In particular, the Bucket RT, is considered the lowest level data available from the gauge (considered for the purpose of this analysis as “raw” data) and
used for this analysis.

2. Test sites and Sensors

2.1 CARE site in Canada

The CARE (Centre for Atmospheric Research and Experiments) site is located in the town of Egbert, province of Ontario, at 44° 17' latitude, 79° 47' longitude and 251 m elevation and belongs to humid continental climate. The daily average temperature is -8.2°C in January and total average annual snowfall is 157 cm. The mean wind speed for the period from November to April is 3.5~4.0m/s (WMO/CIMO 2012a).

The site was configured with one R2G from 2012 to 2016, and with a R2P from 2014 to 2016. A precipitation type sensor (disdrometer) type Thies Laser Precipitation Monitor (LPM) was installed within the R2G in 2013 (Fig. 3a).

2.2 Bratt's Lake site in Canada

The Bratt's Lake site is located in 50° 20' latitude, 104° 71' longitude and 585 m elevation. The Bratt’s Lake precipitation intercomparison facility is located 36 km south of Regina, Saskatchewan, Canada. The site is in an agricultural landscape with surrounding vegetation typically less than 1 m in height. The topographical relief is small, with elevation changing less than 1m per km. With low vegetation and large fetch, the wind speeds at the site are relatively high, with 10 m daily average wind speeds exceeding 5 m/s. Average annual snowfall is approximately 106 cm, with an average annual temperature of 2 °C (WMO/CIMO 2012a).

2.3 Gochang site in Korea

Gochang site is located in 35° 20' latitude 126° 35' longitude, and 52 m elevation. The area
received a lot of snow especially from December to January, which is caused by Northwest airflow associated with the extension of the winter Siberian. All instruments are placed on about 7,000m² flattened area. The average temperature was 3.0℃ in January 2013 (KMA 2013). The Automated Surface Observing System (ASOS) is also operated in the northwest at this site.

Three OTT Pluvio² 200 precipitation gauges and three Geonor T-200B gauges are installed at Gochang site. Each gauge is installed with no shield, in single Alter shield, and in DFIR, respectively from December 2014 (Fig. 3c). All Pluvio gauges used rim heating algorithm provided by manufacture, but all Geonor gauges were not equipped with rim heating for this analysis periods.

2.4 Ancillary measurements

Table 1 summarizes the information on all sensors used to measure the air temperature, wind speed, and relative humidity, on each site. For the ancillary measurements, as presented in Table 1, the following sensors were used: NWS425 (at Base 5A in Fig.3a), RM Yong 5103, and JY-WS161B (at Base 26 in Fig. 3c), for wind speed of CARE, Bratt’s Lake, and Gochang, respectively. HMP155 (at Base 10 in Fig. 3a), HMP45C, WS-T100G1 (Base 23, in Fig. 3c) and EE180 (at Base 24. In Fig. 3c) are used for temperature or relative humidity.

The LPM is a present weather sensor based on an optical laser disdrometer, which measures the size and vertical velocity of the hydrometers falling through a 1mm thick laser light sheet (Lanzinger at al. 2006). In the case of CARE site, LPM (at P4 in Fig. 3a) is used as a precipitation detector and used data is intensity.

3. Data and method

3.1 Study period
The analysis in this paper was conducted using data from two winter seasons, for each of the three test sites. At CARE site, the periods are from 1 December 2014 to 30 April 2015, and 1 December 2015 to 31 March 2016. At Bratt’s Lake, the periods are from 17 January 2015 to 20 May 2015, and 1 December 2015 to 28 March 2016. At Gochang, are from 12 December 2014 to 28 February 2015, and 1 December 2015 to 26 January 2016.

Fig. 4 shows time series of quality controlled (WMO CIMO 2014) 1-minute accumulation data of R2G and R2P, and the air temperature after applying QC processing, for the study period, for all three sites. The blue line is the minutely Geonor data, calculated as the averaged value of the 3-wires, and the red line is the minutely Pluvio² accumulation, calculated based on the Bucket RT report.

Fig. 5 represents the time series of 30-minute averaged horizontal wind speed and relative humidity at three sites, for the study periods. The notable point is that the maximum values of 30-minute averaged wind speed at Gochang (12.5m/s) and Bratt’s Lake (13.9m/s) were marginally higher than those from CARE (9.0m/s).

3.2 QC of accumulated precipitation amount data

The results in this paper are based on the 1-minute accumulation data from the Pluvio² and Geonor gauges were quality-controlled (QCed) applying the SPICE QC methodology (WMO CIMO 2014), which has three steps: min-max outlier filtering, jump filtering, and Gaussian filtering. For a Geonor gauge, the QC process is applied to each of the three vibrating wire transducers, and the final Geonor minutely data is obtained by computing the average of the values from the three transducers. When the data was collected with a 6 second temporal resolution (e.g. CARE), then a 1-minute value is obtained by aggregating (or mean averaging)
the 6 seconds for each 1-minute interval.

Table 1 shows the time resolutions of R2 references, tested periods, whether or not the equipment of rim heating. It is noted that the temporal resolution of raw data from the weighing gauges in the R2 references at CARE and Gochang site were 6 seconds, whereas at Bratt’s Lake the data from the gauges in the R2 reference was collected with 1min resolution. The Bratt’s Lake Geonor minutely data is computed inside the data collection datalogger, from three individual samples taken over the course of one minute from each of the three transducers. No additional filtering is applied. The Pluvio\(^2\) data at Bratt’s Lake is obtained from polling the gauge once a minute. This results in the data of Bratt’s Lake having, possibly, higher noise than the other sites. The second point is that R2G in Gochang was not equipped with rim heating for the periods under study, whereas R2P was heated.

### 3.3 Data sampling and precipitation type

For the comparison of two R2 references R2G and R2P, a 30min sampling interval was used to obtain precipitation intensity. This approach is similar to that used for the data analysis for the SPICE results. All comparisons are made when at least one estimated values of two gauges R2P and R2G has positive value, or all values are greater than or equal to the thresholds \(P_0=0.10, 0.25, 0.50\text{mm/h}\). The horizontal wind speed \(U\), air temperature \(T\), relative temperature \(RH\), and dew point temperature \(Td\) have been averaged over the same precipitation sampling interval of 30 min. The dew point temperature is computed from \(RH\) and \(T\) using a formulation in Wagner et al. (2002).

In this work, the precipitation types were separated in snow, mixed precipitation, and rain, using the following temperature conditions:

\[
\text{precipitation type} = \begin{cases} 
\text{snow} & T < -2.0 \, ^\circ C \\
\text{mixed precipitation} & -2.0 \, ^\circ C \leq T \leq 2.0 \, ^\circ C \\
\text{rain} & T > 2.0 \, ^\circ C 
\end{cases}
\]
The approach of using the air temperature as a condition to separate precipitation type for bias corrections is similar to that used in Yang et al. (1995, 1998).

### 3.4 Method

The comparison analysis between the two reference systems, one using a Geonor gauge, the other using a Pluvio² gauge, is performed by examining the distribution of the differences or ratios of the data from the gauges. The methodology used is based on the recommendations from Standard ASTM D4430-00 (2015).

First, the statistical measures of the difference of two systems, systematic difference $d$, operational comparability $C$, and estimated standard deviation of the differences, are used. The systematic difference $d$ is the mean of the differences in the measurement by the two systems, is defined as:

$$ d = \frac{1}{N} \sum_{i=1}^{N} (x_{at} - x_{bt}) $$

The operational comparability is the root mean square (rms) of the difference between simultaneous readings from the two instruments measuring the same quantity in the same environment, such that:

$$ C = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_{at} - x_{bt})^2} $$

where $N$ is the number of measurements, and $x_{at}$ and $x_{bt}$ are the $i$th measurements of the two instruments. The estimated standard deviation of the difference, $s$, is defined as a standard deviation of the difference between two instruments, that is, $s = \sqrt{C^2 - d^2} = \sigma(x_{at} - x_{bt})$. 


Additionally, the relative systematic difference $Rd$, the relative operational comparability $RC$, and the relative standard deviation $Rs$ are the normalize forms of the three parameters defined above, as their ratio to the average output value of
\[
\frac{1}{2N} \sum_{i=1}^{N} (x_{ai} + x_{bi})
\]
of the two measurement systems.

Second, the performance of reporting the precipitation amount by each of the two instruments was assessed using the ratio of the concurrent values reported by the two gauges, and the measurement of $R2G$ is used as a baseline (the denominator). The quartile statistics, moving averages and transfer functions are used to describe the distribution of these ratios. It is known that quartile statistics are less influenced by outliers than mean and standard deviation (Wilks, D.S.). To display the comparison of quartile statistics, a box plot is used with the lower and upper edges of the box located at first quartile (Q1 or 25th percentile) and the third quartile (Q3 or 75th percentile), respectively. The median (Q2 or 50th percentile) can be an indicator of the bias, also the interquartile range (IQR) is the difference of the Q3 and Q1 is a measure of the dispersion of the distribution.

4. Results

4.1 Environmental conditions

Three non-zero precipitation accumulation thresholds, $P0$, are considered for analysis. These are 0.1mm/h, 0.25mm/h, and 0.5mm/h, respectively. Table 2 summarizes the average environmental conditions (air temperature, $T$, relative humidity, $RH$, and wind speed, $U$), for all the 30min intervals when the precipitation intensities of, both, $R2P$ and $R2G$ are greater than or equal to the threshold $P0$, for different precipitation types, and for all sites in this
study. In column 8, the number of data points is the number of 30min events satisfying the threshold P0 condition.

The results in Table 2, indicate that the averaged horizontal velocity reported at the Bratt’s Lake site is larger than for the other two sites, exceeding 4.8m/s for all precipitation types and all threshold values P0. The averaged relative humidity at Bratt’s Lake is also higher than the other sites except for the rain cases. The temperature and relative humidity of CARE site were the lowest of all sites, during snow events.

Fig. 5 shows the probability density function (PDF) of the number of precipitation events, for an intensity threshold of P0=0.25mm/h, stratified by precipitation rate, wind speed, air temperature, and relative humidity. For all the events, the peaks of frequency appear for wind speeds of 5~6m/s, 2~4m/s, and 1~3m/s, for Bratt’s Lake, CARE, and Gochang site, respectively.

A remarkable point is that the wind speed at Bratt’s Lake site was stronger than on the other two sites, while the precipitation intensities were lower. Lower relative humidity during rain events as one can see in Table 2 and Fig. 6, were also reported.

4.2 Statistical assessment of the difference R2P-R2G

Fig. 7 shows the scatter plots of intensities of R2G and R2P for all sites and precipitations when P0 = 0.25mm/h, together with the statistics parameters, as defined in Section 3.4. In these plots, the x-axis and y-axis represent R2G and R2P, respectively. The first, second, and third row represent CARE, Bratt’s Lake and Gochang sites, respectively. For the CARE site, for all types of precipitation, the two references agreed well, with the correlation coefficient varying from 0.98 for snow events to 0.99 for rain and mixed precipitation, and both, Rd and Rs are smallest among the three sites and all precipitation types. For Bratt’s Lake, the two
gauges agreed for snow as the correlation coefficient was 0.98, while for rain and mixed precipitation events, the correlation coefficient was slightly below, at 0.96; also, the value of $Rs$ is higher than the one of snow type. At Gochang, for snow events, the R2P reports higher amounts than the R2G, approximately 13.7% higher, and the values such as $C$ and $s$ are much larger. It is assumed that the differences noted between R2G and R2P are due to the fact that the Pluvio² gauge was heated while the Geonor was not heated.

4.3 Comparison of sensitivity and noise for different thresholds

Next, the impact of the threshold and of the processing interval on the detection and measurement of precipitation, is assessed. When computing precipitation rate from accumulated values of automatic weighing gauges, it would be important to find an optimal threshold to limit the noise, while avoiding the loss of true data.

Fig. 8 shows the distribution of concurrent 30min values P2G and R2P, respectively, as a function of the dew point temperature, $T_d$, (x-axis), the air temperature, $T$ (y-axis), as well as the threshold $P_0$. The blue circles represent the events when the R2G value is larger than R2P corresponding value, while the red dots represent the events when R2P$>R2G\geq0$. From this figure, it is easy to observe that the agreement between two gauges increases and the shape of distribution is narrowed as the threshold $P_0$, increases. A higher R2P value is noted in the area below the diagonal line, and for lower $P_0$ values. That corresponds to R2P values that are higher than the corresponding R2G values in low relative humidity condition, and for low $P_0$ values.

4.4 Detectability of precipitation

To test the detectability of precipitation by the two gauges in the R2 references, a targeted assessment is conducted using the data from a Thies LPM (Laser Precipitation Monitor), for
the CARE site. The LPM is installed in DFIR shield (P4 in Fig. 3a). The period for this test is from 1 December 2015 to 29 February 2016. The 30min intensity data of LPM is calculated as the 30min average of the 1min precipitation intensities reported by the LPM, reported over the corresponding 30-min interval. Fig. 9 shows the scattered points when one reference is recorded a precipitation, whereas the other do not, for different Td (y-axis) and T (x-axis), and for different threshold values, P0. Similar to Fig. 8, the red dots represent the events when the R2P is larger than R2G, while the blue dots represent the events when values of P2G is larger than R2P. Additionally, the cyan circles represent the events when both the R2G and the LPM have positive values, but R2P has no precipitation (i.e. below the imposed threshold), while the magenta circles represent the events when the R2P and the LPM are positive, and he R2G is below the threshold. When P0=0.1 mm/h the number of data points represented is 175, however decreasing significantly to 37 for a threshold of P0=0.25mm/h. A remarkable result is that the use of the LPM as a second filter is important when P0 ≤ 0.1 mm/h is imposed on the weighing gauge data (Fig. 9a), but its contribution is not noted, with the use of a threshold (Fig.9 b-c). Some red dots are observed below the diagonal line when P0=0.1mm/h, which indicates that in lower relative humidity conditions, signal is detected by the R2P but the R2G, which in fact could include some noise. Fig. 9d presents the cases when the R2P response appears noisy (non-zero values were determined), although the LPM reports no accumulation of precipitation.

Table 3 summarizes the number of 30-min events when (a) a weighing gauge and the LPM detect precipitation (Hit), (b) a weighing gauge detects precipitation but LPM does not (False), (c) LPM detect precipitation but the weighing gauge does not (Miss), and (d) both the weighing gauge and LPM do not detect precipitation. This analysis was conducted for each of
the two weighing gauges, and for different P0 values. The intensity data of LPM has a very
fine resolution, 0.001 mm/h. When no threshold is applied for the 30-min events from the
LPM, many small amount data are included in the 30-min sample data of LPM. This is the
reason for the very high number of ‘Miss’ events compared to ‘False’ data. The ratio a/(a+b)
is presented in Fig. 10 as a bar graph. In this figure, when P0 = 0.1mm/h the ability to detect
precipitation of R2P is 92%, and for R2G is 100%, both reaching 100% for thresholds of
0.25mm/h and above.

4.4 Assessment of the R2P/R2G ratio

Figs. 11~13 show the distribution of the ratio R2P/R2G, R, as colored levels, in two-
dimensional flat surfaces, for the variables: wind speed U, air temperature T, and relative
humidity RH. The color scale represents the magnitude of R for each set of conditions, using
moving average values. Fig. 11 shows the moving average values of CR at (U, T) points in
the region [U-1, U+1] x [T-2, T+2]. Similarly, Fig. 12 and Fig. 13 represent the average
values of CR at point (RH, T) in the region [RH-2, RH+2] x [T-2, T+2], and at (U, RH) in
the region [U-1, U+1] x [RH-2, RH+2].

As the P0 is increased the two values, R2P and R2G approach each other. For example,
for the Bratt’s Lake results, the occurrence of events R2P>R2G, for low temperatures and
with strong wind speeds decreases notably by increasing the threshold P0 (see Fig. 12). As
noted in Fig. 12, in the mixed type condition (around 0°C temperature), and with low
relative humidity conditions, events with R2P>R2G are still present, but to a lower degree.
In Figs. 11 and 12, at Gochang site, the events R2P>R2G also clearly observed in low
temperature, likely due to the no rim heating of R2G. For CARE, for threshold values at or
above 0.1mm/h, the values reported by the two gauges have a close agreement.
Further analysis of these events is conducted stratifying the data by precipitation type, and using quartile statistics. The median and the IQR are examined in more details, to characterize the relative values of R2P versus R2G, and their spread, as a function of the selected threshold, P0, at 0.1 mm/h, 0.25 mm/h, and 0.5 mm/h.

### 4.4.1 Quartile Statistics for Rain Events

Quartile statistics are presented for the rain type precipitation cases in Table 4 and Fig. 13a, for different thresholds. For the CARE results, the medians of the ratio R are equal to 1.00 for all thresholds, meaning that biases were not detected. For Gochang, relatively constant, the values hover around 0.95, indicating slightly larger amount reported by the Geonor based DFAR. For Bratt’s Lake, the median of the ratio varies between 0.88 and 0.97, depending on threshold, meaning that the R2P is slightly below the R2G value. The IQR is also indicative of the relative distribution of the values reported by the two gauges. For all P0 values, the IQR is at or below 14% for CARE and Gochang, while for Bratt’s Lake is at or below 33%. When P0=0.5mm/h, the IQR at Bratt’s Lake is about 27% which is still larger than the 7% and 8% of other two sites.

### 4.4.2 Quartile Statistics for Mixed Precipitation Events

For mixed precipitation type, the quartile statistics are presented in Table 5 and Fig. 14b, for the same thresholds, as above. The results from CARE and Gochang appear quite similar. For CARE, R2P is slightly higher than R2G, with median values of 104~105 %, for all thresholds, whereas, the IQR of about 8% is the smallest among the three sites. For Gochang, R2P is slightly higher than R2G and the IQR decreases as the P0 is increased. The Bratt’s Lake results show medians of 91% for P0=0.1mm/h, increasing to 0.96 for P0=0.5 mm/h; at the same time, the IQR varies from 32%, for P0=0.1 mm/h to 17% for P0=0.5mm/h.
4.4.3 Quartile Statistics for Snow Events

As noted in the previous sections, R2G gauge at Gochang site was not equipped with any rim heating, which led to large differences being noted between concurrent R2P and R2G values. This can be seen from Table 6, and Fig. 14c, as well, with the IQR much larger than for the other sites. For CARE and Bratt’s Lake, the median (Q2) varies between 0.95 to 0.98 for all P0 at or above 0.1 mm/h. The IQR of CARE and Bratt’s Lake are about 11% and 10%, respectively, for fixed P0=0.5mm/h.

4.5 Statistical values of the difference R2P-R2G

The relative systematic difference $R_d$ and relative standard deviation $R_s$ are examined for the data from the two automatic gauges, R2P and R2G, by varying P0.

4.5.1 Rain Events

For rain events, as one can see in Fig. 15a and Table 7, $R_d$ and $R_s$ at CARE and Gochang have similar values. The systematic difference $R_d$ is relatively stable around 1%, and -4% at CARE and Gochang, respectively, as P0 is increased from 0.1 to 0.5mm/h. The $R_d$ of Bratt’s is almost stable as -10% when P0≥0.1 mm/h. The relative standard deviation $R_s$ for Bratt’s Lake is decreased from 27.2% for P0=0.1mm/h to 18.6% for P0=0.5mm/h. The $R_s$ for CARE and Gochang are below 10% at P0=0.5mm/h.

4.5.2 Mixed Precipitation Events

In Fig. 15b and Table 7, all $R_d$ of CARE have positive values (i.e. R2P > R2G) for all P0. Whereas, Bratt’s Lake have negative values of Rd when P0≥0.1 mm/h. At Gochang, the $R_s$ for all P0 have a little larger values than rain type.

4.5.3 Snow

Fig. 15c and Table 7 show the correlation coefficients, Rs, and Rd between two gauges in
snow type. Bratt’s and CARE sites have almost stable values of \( R_d \) and \( R_s \) when \( P_0 \geq 0.1 \) mm/h. When \( P_0 = 0.5 \) mm/h, the \( R_d \) of CARE and Bratt’s Lake are -1.8% and 3.8%, respectively, whereas Gochang have 13% overestimation of \( R_2P \). The \( R_s \) of CARE and Bratt’s Lake are 10% and 15%, respectively, whereas, \( R_s \) of Gochang is 40% due to the no heating of \( R_2G \). In Table 7, the correlation coefficients of CARE, Bratt’s Lake, and Gochang are about 0.9861, 0.9838, and 0.6670, respectively when \( P_0 = 0.5 \) mm/h.

4.6 Development of \( R_2P/R_2G \) Transfer function

The results assessed show that \( R \) varies with the threshold \( P_0 \), as well as the air temperature \( T \), and the relative humidity \( RH \). In this section, for snow events, as well as for all types, linear transfer functions are considered using linear regression analysis. All transfer functions are computed using the fixed threshold \( P_0 = 0.5 \) mm/h, and as a function of temperature, relative humidity or wind speed.

4.6.1 Transfer functions for snow type

We assume that the ration function \( R \) is linear function of first order of \( T \), \( RH \), and \( U \) such that

\[
R(T, RH, U) = a_0 + a_1T + a_2RH + a_3U
\]

The coefficients of this linear equation can be found easily using regression analysis. The computed regression equation of the CARE, the Bratt’s Lake, and combined, are

\[
R = 1.2524 + 0.0086T - 0.0022RH + 0.0012U \quad (N = 204, \ r^2 = 0.9741),
\]

\[
R = 1.7389 + 0.0105T - 0.0073RH - 0.0048U \quad (N = 56, \ r^2 = 0.9674),
\]

and

\[
R = 1.5133 + 0.0103T - 0.0049RH - 0.0046U \quad (N = 260, \ r^2 = 0.9731),
\]

respectively. After applying these regression equations, the operational comparability \( C \)
between two gauges are decreased from 0.1412 mm/h (10.75%) to 0.1350 mm/h (10.32%) at CARE site. Using the regression equation of the Bratt’s Lake, C is also decreased from 0.1548 mm/h (12.71%) to 0.1515 mm/h (12.43%). Next, from the regression equations of two site, the C of all 260 data of two sites is decreased from 0.1442 mm/h (11.98%) to 0.1360 mm/h (10.52%).

In the above three equations, all absolute values of coefficients of U in three equations are relatively small compared those for T, RH. Leaving out the wind speed U term, the following first order regression equation is used

\[ R(T,RH,U) = a_0 + a_1T + a_2RH \]

Similar way, the linear regression equation for the CARE site is

\[ R = 1.2720 + 0.0086T - 0.0024RH \ (N = 204, r^2 = 0.9743) \]

and that for the Bratt’s Lake is

\[ R = 1.5687 + 0.0105T - 0.0058RH \ (N = 56, r^2 = 0.9684) \]

Lastly, using the all data of the Bratt’s Lake site and the CARE site, we found the first order regression equation

\[ R = 1.5476 + 0.0107T - 0.0054RH \ (N = 260, r^2 = 0.9726) \]

The linear regression equations and ratio points are represented in Fig. 15a-15c. From the regression equations without velocity term U, the values of C between two gauges are changed from 0.1350 mm/h (10.32%) to 0.1345 mm/h (10.28%) at CARE site (see Fig. 15a), from 0.1515 mm/h (12.43%) to 0.1481 mm/h (12.42%) at Bratt’s Lake site (see Fig. 15b), and from 0.1360 mm/h (10.52%) to 0.1372 mm/h (10.70%) at both sites (see Fig. 15c). In these linear regression equations in Fig 15a-15c, one can observe the common patterns in all sites: for snow type, the ratio R2P/R2G is a little increased when RH is decreased and T is
increased.

4.6.1 Transfer functions for all precipitation type

We also consider transfer function for all precipitation typed by assuming the regression equation is the following second order form

\[ R(T, RH) = a_0 + a_1 T + a_2 T^2 + a_3 T \cdot RH + a_4 RH + a_5 RH^2 \]

As regression equations, we found

\[
R = 1.5823 - 0.0037T - 0.0003T^2 + 0.0000T \cdot RH - 0.0117RH + 0.0001RH^2
\]

\((N = 488, r^2 = 0.9866)\)

\[
R = 0.8669 - 0.0246T - 0.0008T^2 + 0.0003T \cdot RH + 0.0089RH - 0.0001RH^2
\]

\((N = 107, r^2 = 0.9492)\)

for the CARE site and Bratt’s Lake site, respectively. Using the both data of two sites, the second order transform equation is

\[
R = 1.4318 - 0.0176T - 0.0004T^2 + 0.0002T \cdot RH - 0.0065RH - 0.0000RH^2
\]

\((N = 595, r^2 = 0.9825)\)

From the regression equations, the operational comparability C between two gauges are changed from 0.132 mm/h (9.03%) to 0.1303 mm/h (8.87%) at CARE site, from 0.1867 mm/h (15.12%) to 0.1753 mm/h (14.14%) at Bratt’s Lake, and from 0.1437 mm/h (13.11%) to 0.1423 mm/h (9.97%) at both sites. In these second order equations, the coefficients of \(T \cdot RH\) and \(RH^2\) are very small compared to other terms. When removing the \(T \cdot RH\) and \(RH^2\) terms, the equations for CARE site and Bratt’s Lake site are computed as

\[
R = 1.1354 + 0.0009T - 0.0003T^2 - 0.0012RH (N = 488, r^2 = 0.9869)
\]

and

\[
R = 1.4210 - 0.0004T - 0.0008T^2 - 0.0045RH (N = 107 r^2 = 0.9485),
\]
respectively. Using the data of CARE and Bratt’s sites, the second order transform equation is

\[ R = 1.2082 + 0.0010T - 0.0003T^2 - 0.0021RH \quad (N = 595 \, r^2 = 0.9829) \]

These regression equations are presented in Fig.15d-15f. Using the first order RH regression equations, the operational comparability C between two gauges are changed from 0.1303 mm/h (8.87%) to 0.1289 mm/h (8.75%) at CARE site (see Fig. 15d), from 0.1753 mm/h (14.14%) to 0.1764 (14.52%) at Bratt’s Lake (see Fig. 15e), and from 0.1423 mm/h (9.97%) to 0.1407 mm/h (9.87%) at both sites (see Fig. 15f). As a result, in the regression equations in Fig 15, the ratio has maximum value near 0°C in low relative humidity condition.

5. Summary and conclusion

In this study, data from two winter seasons for three sites, are analyzed to investigate the systematic differences and the noise level, that would allow to characterize the performance of the SPICE R2 reference system as a function of the atmospheric conditions. One important result is that of assessing to which degree the R2 values vary with the type of gauge used in the R2 reference system. The 30-min precipitation intensity data were compared as a function of the precipitation types, some environmental conditions, and different thresholds of accumulated precipitation. We observed that each reference and their difference are quite sensitive to thresholds and, likely, the heating of rim. The difference can be reduced to a certain extent by increasing the threshold and two references, as long as both gauges are heated. For a threshold of P0 = 0.5 mm/h, in the rain type, the Rs at CARE site was smallest as 7.0%, and the next was Gochang as 7.4%, and Bratt’s Lake 18.5%. In the mixed precipitation type, the Rs of CARE site was also smallest among three sites as 8.3%, the next was 14% of Bratt’s Lake, and 18.9% of Gochang. In the snow type, the Rs of CARE, Bratt’s Lake, were 10.6%, 12.2%. The Gochang was 40.0%, likely due to the difference in the
heating of the two gauges. Relatively large $Rs$ of Gochang site in mixed or snow type is due to the no equipment of rim heating for R2G.

Through the analysis of ratios, the effects of a threshold and atmospheric conditions were examined as a quartile analysis and moving average analysis. The results have shown that with the increase in threshold, the scatter of the differences between concurrent values of the reference system using either of the two gauges, decreases significantly.

For snow precipitation type and for all types, transfer functions dependent on T, RH were considered using linear regression analysis. After applying these transfer function, the operational comparability $C$ was compared with values prior to the application of the transfer function proposed. As a result, when $P0=0.5\text{mm/h}$, R2P is averagely underestimated than R2G in rim heating condition but a littler overestimation is appeared in low relative humidity condition near the temperature 0°C.

Acknowledgements. This work was funded by the Korea Meteorological Administration Research and Development Program under Grant KMIPA 2015-1010.
References


Table 1. Time resolutions of each R2 reference and used sensors for wind speed and temperature conditions.

<table>
<thead>
<tr>
<th></th>
<th>CARE</th>
<th>Bratt’s Lake</th>
<th>Gochang</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period(UTC), [dd/mm/yy]</strong></td>
<td>01/12/14<del>30/04/15 01/12/15</del>31/03/16</td>
<td>17/01/15<del>20/05/15 01/12/15</del>20/03/16</td>
<td>12/12/14<del>28/02/15 01/12/15</del>26/01/16</td>
</tr>
<tr>
<td><strong>Time resolutions of R2G and R2P</strong></td>
<td>6ses</td>
<td>1min</td>
<td>6ses</td>
</tr>
<tr>
<td><strong>Rim heating</strong></td>
<td>All heated</td>
<td>All heated</td>
<td>R2G : not heated</td>
</tr>
<tr>
<td><strong>Temperature (height)</strong></td>
<td>Vaisala HMP155 (1.5m)</td>
<td>Campbell HMP45C (1.5m)</td>
<td>WS-T100G1 (1.6m)</td>
</tr>
<tr>
<td><strong>Relative Humidity (height)</strong></td>
<td>EE180 (1. m)</td>
<td></td>
<td>EE180 (1. m)</td>
</tr>
<tr>
<td><strong>Wind speed (height)</strong></td>
<td>Vaisala NWS425 (2m)</td>
<td>RM Young 5103 (2.2m)</td>
<td>JY-WS161B (m)</td>
</tr>
</tbody>
</table>
Table 2. Number of 30-minute sampling events, average values of temperature, relative humidity, and wind speed for different precipitation types.

<table>
<thead>
<tr>
<th>P0 [mm/h]</th>
<th>Type</th>
<th>Site</th>
<th>T [°C]</th>
<th>RH [%]</th>
<th>U [m/s]</th>
<th>PI [mm/h]</th>
<th># of data</th>
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<td>Rain</td>
<td>CARE</td>
<td>5.76</td>
<td>90.62</td>
<td>2.98</td>
<td>1.02</td>
<td>274</td>
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<td>86.52</td>
<td>4.72</td>
<td>0.71</td>
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<td>94.46</td>
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<td>0.81</td>
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<td>0.89</td>
<td>269</td>
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<td></td>
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<td>-0.03</td>
<td>96.00</td>
<td>5.38</td>
<td>0.48</td>
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<td>130</td>
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<td>Snow</td>
<td>CARE</td>
<td>-9.23</td>
<td>84.93</td>
<td>3.40</td>
<td>0.62</td>
<td>582</td>
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<td>4.51</td>
<td>0.46</td>
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<td>0.64</td>
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<td>Rain</td>
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<td>90.71</td>
<td>3.17</td>
<td>1.25</td>
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<td>Bratt’s Lake</td>
<td>6.77</td>
<td>87.71</td>
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<td>94.93</td>
<td>3.16</td>
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<td>96.34</td>
<td>3.63</td>
<td>0.89</td>
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<td>CARE</td>
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<td>118</td>
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<td>92.87</td>
<td>4.02</td>
<td>0.78</td>
<td>126</td>
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<td>0.50</td>
<td>Rain</td>
<td>CARE</td>
<td>5.83</td>
<td>91.20</td>
<td>3.10</td>
<td>1.58</td>
<td>155</td>
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<tr>
<td></td>
<td></td>
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<td>6.05</td>
<td>90.74</td>
<td>4.88</td>
<td>1.33</td>
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<tr>
<td></td>
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<td>7.21</td>
<td>95.66</td>
<td>3.27</td>
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<td>92.77</td>
<td>3.15</td>
<td>1.58</td>
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<td>3.89</td>
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</table>
Table 3. The number of detection of R2P and R2G when LPM is used as a reference. The period for analysis is same as the Fig. 8 and Fig. 9.

<table>
<thead>
<tr>
<th>P0 [mm/h]</th>
<th>Hit (a) R2≥P0, LPM&gt;0</th>
<th>False (b) R2≥P0, LPM=0</th>
<th>Miss (c) R2&lt;P0, LPM&gt;0</th>
<th>Correct negative (d) R2&lt;P0, LPM=0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R2G</td>
<td>R2P</td>
<td>R2G</td>
<td>R2P</td>
</tr>
<tr>
<td>0.10</td>
<td>605</td>
<td>594</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>0.25</td>
<td>387</td>
<td>377</td>
<td>0</td>
<td>1</td>
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<tr>
<td>0.50</td>
<td>245</td>
<td>250</td>
<td>0</td>
<td>0</td>
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Table 4. The quartile statistics of ratio distributions for different thresholds when the precipitation is rain.

<table>
<thead>
<tr>
<th>Site</th>
<th>P0 [mm/h]</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARE</td>
<td>0.10</td>
<td>0.93</td>
<td>1.00</td>
<td>0.07</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.95</td>
<td>1.00</td>
<td>1.06</td>
<td>0.11</td>
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<tr>
<td></td>
<td>0.50</td>
<td>0.97</td>
<td>1.00</td>
<td>1.05</td>
<td>0.08</td>
</tr>
<tr>
<td>Bratts</td>
<td>0.10</td>
<td>0.74</td>
<td>0.88</td>
<td>1.07</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
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<td>0.91</td>
<td>1.09</td>
<td>0.29</td>
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<tr>
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<td>0.83</td>
<td>0.97</td>
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<td>Gochang</td>
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<td>0.86</td>
<td>0.95</td>
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<tr>
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<td>0.95</td>
<td>1.00</td>
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<tr>
<td></td>
<td>0.50</td>
<td>0.93</td>
<td>0.96</td>
<td>1.00</td>
<td>0.07</td>
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Table 5. The quartile statistics of ratio distributions for different thresholds when the precipitation type is mixed.

<table>
<thead>
<tr>
<th>Site</th>
<th>P0 [mm/h]</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARE</td>
<td>0.10</td>
<td>0.97</td>
<td>1.045</td>
<td>1.15</td>
<td>0.19</td>
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<td>1.05</td>
<td>1.14</td>
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<tr>
<td></td>
<td>0.50</td>
<td>1.00</td>
<td>1.04</td>
<td>1.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Bratt’s Lake</td>
<td>0.10</td>
<td>0.75</td>
<td>0.91</td>
<td>1.07</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.83</td>
<td>0.94</td>
<td>1.08</td>
<td>0.32</td>
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<tr>
<td></td>
<td>0.50</td>
<td>0.90</td>
<td>0.96</td>
<td>1.06</td>
<td>0.17</td>
</tr>
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<td>0.81</td>
<td>0.93</td>
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<td>0.96</td>
<td>1.03</td>
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<td>0.97</td>
<td>1.05</td>
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Table 6. The quartile statistics of ratio distributions for different thresholds when the precipitation type is snow.

<table>
<thead>
<tr>
<th>Site</th>
<th>P0 [mm/h]</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARE</td>
<td>0.10</td>
<td>0.88</td>
<td>0.96</td>
<td>1.04</td>
<td>0.17</td>
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<td>0.25</td>
<td>0.91</td>
<td>0.96</td>
<td>1.03</td>
<td>0.13</td>
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<td>0.93</td>
<td>0.98</td>
<td>1.04</td>
<td>0.11</td>
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<td>Bratt’s Lake</td>
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<td>0.86</td>
<td>0.96</td>
<td>1.03</td>
<td>0.18</td>
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<tr>
<td></td>
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Table 7. Statistical values of R2P-R2G for different precipitation types and thresholds of 30-min sampling sets.

<table>
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<th>Type</th>
<th>Site</th>
<th>P₀ mm/h</th>
<th>CORR</th>
<th>d mm/h</th>
<th>Rd %</th>
<th>C mm/h</th>
<th>RC %</th>
<th>s mm/h</th>
<th>Rs %</th>
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<td>-4.1</td>
<td>0.01</td>
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Fig. 1. DFAR Cross-section (drawing J Hoover, Environment Canada).
Fig. 2. (a) Use of Weighing Type Gauges (2008 CIMO Survey, Nitu and Wong, 2010).

Photos of (b) Geonor T200-B3 and (b) OTT Pluvio2. (Courtesy by Environment Canada)
Fig. 3. Site layouts of (a) CARE site (November 20, 2014~ Present), (b) Bratt’s Lake site, and (c) Gochang site (December 12, 2014~ Present).
(a) 2014-2015
(b) 2015-2016

Fig. 4. QCed accumulation data of R2G and R2P, and 1 min temperature at CARE (first row), Bratt’s Lake (second row), and Gochang sites (third row) in (a) 2014-2015 winter and (b) 2015-2016 winter. At CARE site, total accumulations were around 200 mm and 300 mm in 14-15 and 15-16 winter seasons, respectively. Bratt’s Lake site had around 90 mm precipitation amount, and unfortunately, did not have much snow during the 2015-16 winter. The black circle is the period from 14 12:00 UTC February 2015 to 15 6:00 UTC February 2015 which is excluded for analysis due to a snow blowing event. At the Gochang site, about 100 mm of precipitation was accumulated for each year.
Fig. 5. Time series of 30-min averaged wind speed and relative humidity at CARE (first row), Bratt’s Lake (second row), and Gochang sites (third row) in (a) 2014-2015 winter and (b) 2015-2016 winter.
Fig. 6. Probability density function (PDF) for precipitation intensity, wind speed, environmental temperature, and relative humidity of the 30 averaged data of three sites when $P_0 = 0.25 \text{ mm/h}$. 
Fig. 7. Scatter plots of R2G and R2P for all sites and all types when P0 = 0.25 mm/h. The first row is CARE site, the second is Bratt’s Lake, and the third row is Gochang site. The correlation coefficient CORR, systematic difference d (relative systematic difference Rd), operational comparability C (relative operational comparability RC), and standard deviation s (relative standard deviation Rs) are represented as the texts in this plot.
Fig. 8. Scatter plots of temperature (x-axis) and dew-point temperature (y-axis) when R2P and R2G have different precipitations by varying the threshold P=0.1, 0.25, and 0.5 mm/h. Red dots and blue circles represent the events of different precipitation amount: R2P > R2G and R2P < R2G, respectively.
Fig. 9. Scatter plots of temperature (x-axis) and dew-point temperature (y-axis) when one of R2P and P2G has detected a precipitation but the other has not. Cyan dots and magenta dots represent LPM also have precipitation. The LPM is the one in DFIR-fence with R2G, and the test period is from 1 December 2015 to 23 March 2016.
Fig. 10. Detectability of R2P (red bar) and R2G (blue bar) for difference thresholds when LPM is used as a reference. The test period is the same as the Fig. 9.
Fig. 11. Moving average of the ratio $R = \frac{R_2P}{R_2G}$ for different thresholds ($P_0 = 0.1$, 0.25, and 0.5 mm/h), temperature $T$ (y-axis), and wind speed $U$ (x-axis). Red color and blue color represent the events of $R_2P > R_2G$ and $R_2P < R_2G$, respectively. Moving average width is 2 m/s for $U$ and 4°C for $T$. The first row is CARE, second is Bratt’s Lake, and third row is Gochang site.
Fig. 12. Moving average of the ratio $R = R_{2P}/R_{2G}$ for different thresholds ($P_0 = 0.1$, $0.25$, and $0.5$ mm/h), temperature $T$ (y-axis), and relative humidity $RH$ (x-axis). Moving average width is 4\% for RH and 4°C for T. Red color and blue color represent the events of $R_{2P} > R_{2G}$ and $R_{2P} < R_{2G}$, respectively. The first row is CARE, second is Bratt’s Lake, and third row is Gochang site.
Fig. 12. Moving average of the ratio $R = R_{2P}/R_{2G}$ for different thresholds ($P_0 = 0.1$, 0.25, and 0.5 mm/h), relative humidity RH (y-axis), and wind speed U (x-axis). Moving average width is 4 % for RH and 2 m/s for U. Red color and blue color represent the events of $R_{2P} > R_{2G}$ and $R_{2P} < R_{2G}$, respectively. The first row is CARE, second is Bratt’s Lake, and third row is Gochang site.
Fig. 13. Box plots of ratio distributions using 30-minute intensity data for different precipitation types (a) rain, (b) mixed precipitation, (c) snow, and for different thresholds: P0= 0.1, 0.25, and 0.5 mm/h.
Fig. 14. Relative systematic difference Rd (left) and relative standard deviation (Rs) of the difference R2P-R2G by increasing the threshold P0 for different precipitation types: (a) rain, (b) mixed, and (c) snow.
Fig. 15. Plots of ratio R and their regression equation as a function of temperature T and relative humidity RH when P0=0.5 mm/h. (a) When the precipitation type is snow, the linear regression equations for CARE site is $1.2720+0.0086T-0.0024RH$, (b) For Bratt’s Lake is $1.5687+0.01057T-0.0058RH$, and (c) $1.5476+0.0107T-0.0054RH$ is for both the two sites. For all types, the second order of T and first order RH regression equations for the CARE, the Bratt’s Lake, and both two sites are (d) $1.1354+0.0009T-0.0003T^2-0.0012RH$, (e) $1.4210-0.0004T-0.0008T^2-0.0045RH$ and (f) $1.2082+0.0010T-0.0003T^2-0.0021RH$, respectively.