The relationship between manual and Geonor automatic gauge measurements of solid precipitation in DFIR shields during SPICE[1]

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Abstract

The World Meteorological Organization (WMO) Solid Precipitation Intercomparison Experiment (SPICE) aims to make recommendations for an automated field reference system for solid precipitation measurements, and is expected to be completed by 2015. As a part of this project, a standard Double Fence Intercomparison Reference (DFIR) with a manual Tretyakov gauge and an automatic field reference with a Geonor T-200B3 gauge within a DFIR shield were installed at the Centre for Atmospheric Research Experiments (CARE) field measurement site in Egbert, Ontario, Canada. This paper presents an analysis of the relationship between the reference systems of DFIR with a manual gauge and DFIR with an automatic gauge for measurements of solid precipitation, based on data from the winters of 2012-2013 and of 2013-2014. This work is intended to establish a link between the manual and Geonor automatic gauge measurements within the DFIR.

1 Introduction

As a part of the WMO-SPICE project, a standard DFIR ([7]), consisting of an octagonal vertical double fence shield and a manual Tretyakov gauge at the centre, and an automatic field reference with a Geonor T-200B3 gauge within a standard DFIR double fence shield were installed at the CARE field site in Egbert, Ontario, Canada. In the SPICE project the DFIR with the manual Tretyakov gauge is termed the 'R1 reference', and the DFIR with the Geonor automatic gauge the 'R2 reference'.

The weight of the precipitation collected in the manual gauge in the R1 reference between observations is measured with a scale, and the Snow to Water Equivalent (SWE) amount is then computed using the density of water and the collecting area of the gauge. The manual observation of R1 reference varies mainly from 20 to 29 hours, with the average equal to about 24 hours.

The three transducers of R2 Geonor gauge are sampled every 6 seconds. Maximum, minimum, and jump filters are applied to the frequency data to remove any outliers. The filtered frequency data for each

[1] SPICE disclaimer: Results presented in this work were obtained as part of the Solid Precipitation Inter-Comparison Experiment (SPICE), conducted on behalf of the World Meteorological Organization (WMO) Commission for Instruments and Methods of Observation (CIMO). The analysis and views described herein are those of the author(s) at this time, and do not necessarily represent the official outcome of WMO SPICE. Mention of commercial companies or products is solely for the purposes of information and assessment within the scope of the present work, and does not constitute an endorsement by the author(s) or WMO.

transducer is converted to a precipitation amount using the formula and constants supplied by the manufacturer. Noise and artefact in the R2 precipitation amounts are then analyzed. A one-minute, moving average is applied to the R2 transducer amounts to remove some of the high frequency noise. The R2 reference amount is then computed as the average of the three transducer amounts.

The objective of this work is to derive the Catch Efficient (CE) of R2 with respect to R1, that is, the ratio of an R2 increment over an R1 increment over the same observation period, for solid precipitation. The dependence of CE on wind speed is investigated. The effect of temperature on the R2 measurements and frost on the R1 measurements are also considered.

2 R1 vs. R2 Intercomparison

2.1 Equipment

2.1.1 R1

The Tretyakov manual gauge of the R1 reference has a collecting area of 200 cm^2, and is shown in Figure 1. More details can be found in [2].

Figure 1: R1 Tretyakov manual gauge (taken from [2]).

2.1.2 R2

The Geonor T-200B3 automatic gauge in the R2 reference is installed inside a single Alter shield, as shown in Figure 2. This Geonor is Environment Canada owned gauge. The Geonor gauge is equipped with three transducers and rim heating in the manner of USCRN ([1]). The gauge has a collecting area of 200 cm^2 and a capacity of 600 mm.

Figure 2: R2 Geonor automatic gauge (taken from [2]).

2.1.3 Wind

The wind information for this work are obtained from two Vaisala NWS425 ultrasonic wind sensors at the CARE site, one at the height of 2 metres and the other at 3 metres.

2.1.4 Temperature

The ambient air temperature at the CARE site is measured by a Yellow Springs International (YSI) Model 44212 thermistor in a Stevenson Screen, and also by another YSI44212 thermistor within the R2 double fence near the Geonor gauge.

2.1.5 Present Weather Sensors

The information from two present weather sensors at the CARE site, an OTT Parsivel present weather sensor and a Vaisala PWD22 present weather detector, are also used.

2.1.6 CARE Site Layout

The CARE site layout is shown in Figure 3, with the locations of the instruments described above.

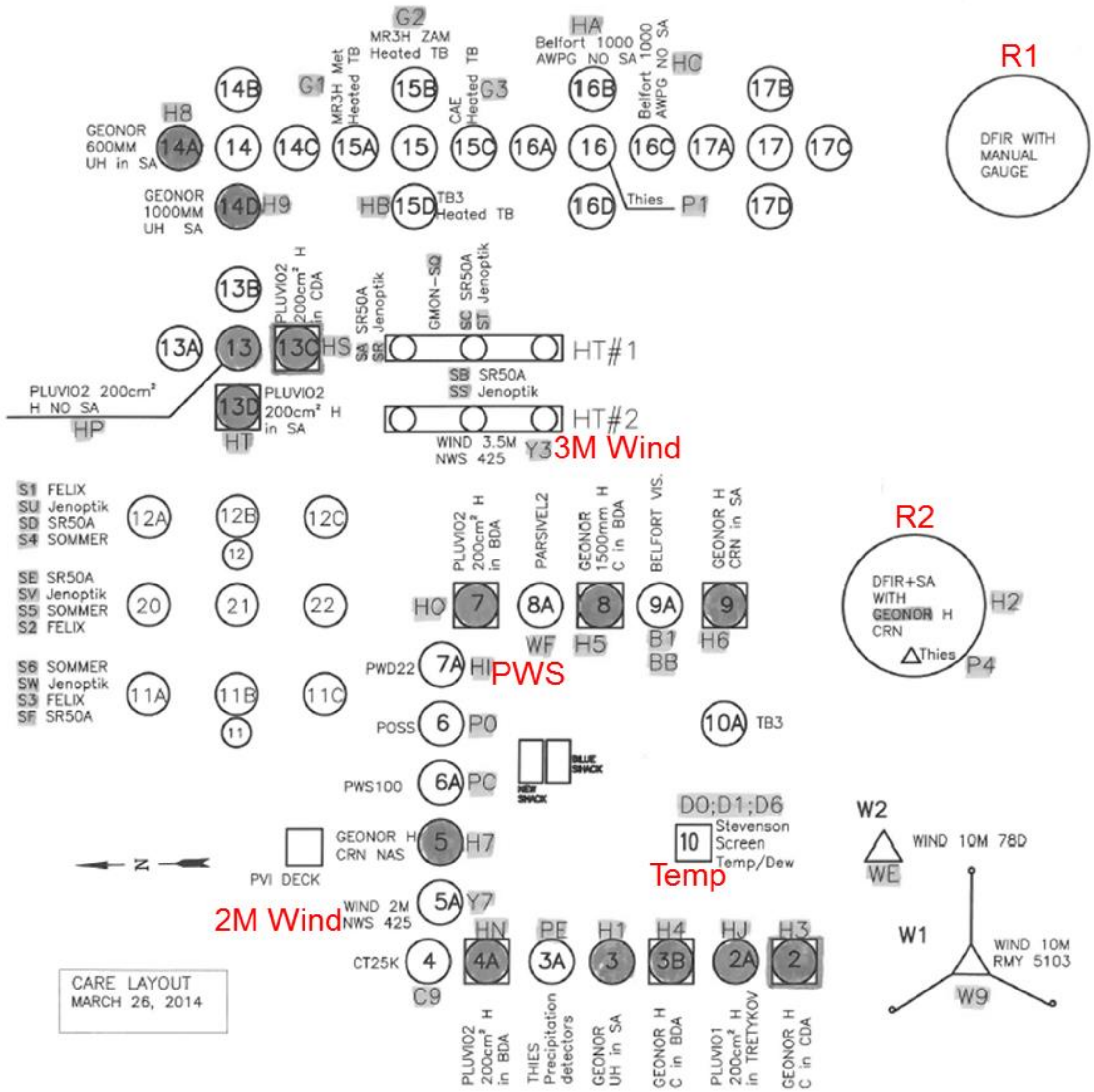


Figure 3: CARE site layout.

The distance between R1 and R2 is about 36 m.

2.2 Data

2.2.1 QC Procedures

The data that is used for the analysis is quality controlled by using max, min and jump filters to remove any outliers. The limits for these filters are given below.

2.2.2 R1 Data

The observation of R1 was made in accordance with the manual observation procedures set out in [5]. It should be noted that the procedures in [5] differs from the traditional observation of a DFIR, in that the weight, instead of the volume as in the traditional observation, of the collected precipitation is measured. This is done by measuring with a scale the empty gauge before deploying it in the field and the gauge with collected precipitation after bringing it back from the field and removing any precipitation adhering to the outside of the gauge ([5]).

The scale used is an Ohaus Explorer analytical and precision balance, with a capacity of 10,200 g ([9]), with readability, repeatability and linearity of 0.1 g. The scale was calibrated in January 2012 and July 2013 with calibration error below 0.1 g in both cases. The calibration reports are given in [10].

The SWE, snow to water equivalent, amount in millimetres is computed from the weight of the precipitation collected using the density of water and the dimensions of the collector ([5]) as follows.

$$SWE = \frac{M}{\rho A} = \frac{M}{1g/cm^3 \times 200cm^2} = (0.005cm/g) \times M = (0.05mm/g) \times M$$

where ρ is the density of water and is assumed to be constant and equal to 1 g/cm^3, A is the collecting area and is assumed to be 200cm^2, and M is the weight of the precipitation collected in grams.

At the CARE site the manual SWE amount is reported to the hundredth of one millimetre. Assume the uncertainty of the scale to be 0.1 g, as one standard deviation, and the collecting area to be exactly 200cm^2, ignoring any uncertainty in it. It can be derived that the laboratory uncertainty of SWE is 0.01 mm.

The R1 observation was made between December 8, 2012 and April 9, 2013, and between December 4, 2013 and April 1, 2014. In the month of December 2013 the manual observation was sparse with only 9 observations and the longest period between observations was about 10 days. Other than this month the observation periods varied mainly from 20 to 29 hours, with the average equal to 24 hours, the minimum 7 hours and the maximum 47 hours.

The max, min and jump filters were not applied to the R1 precipitation amounts.

2.2.3 R2 Data

The R2 transducer frequencies are sampled every 6 seconds, and on the basis of these sampled frequencies the precipitation amounts in the bucket are calculated using the formula given in ([6]):

$$P = A(f - f_0) + B(f - f_0)^2$$

where P is the precipitation amount in the bucket in centimetres, f is the frequency reading in Hertz, A and B are calibration constants, and f_0, also a calibration constant, is the frequency (in Hertz) when the bucket is empty.

The manufacturer-supplied calibration constants and empty bucket frequencies for R2 are:

North (S/N 12512): A = 0.0167911, B = 9.14335E-06, f_0 = 1051.7.

South East (S/N 12812): A = 0.0166180, B = 9.16127E-06, f_0 = 1063.6.

South West (S/N 13312): A = 0.0166875, B = 9.13974E-06, f_0 = 1064.3.

Judging from the Section 5.4 of [6] of checking the function of the transducer the water density used by Geonor appears to be also 1 g/cm^3.
The max, min and jump filters are applied to the R2 transducer frequencies with the following limits: max 3000 Hz, min 1000 Hz, and jump 20 Hz per 6 seconds.

2.2.4 Wind, Temperature and Present Weather Sensors

The wind and present weather sensors are sampled every minute, and the temperature sensor every half of a minute.

The max, min and jump filter limits for wind and temperature sensors are:

Temperature: max 50°C, min -40°C and jump 0.5°C per 30 seconds.

Wind: max 155 m/s, min 0 m/s and jump 10 m/s per minute.

3 Preliminary Results

3.1 Noise and Artefact

The variation in the R2 transducer precipitation amount may be caused by wind, temperature, or other random factors.

We first look at examples of wind effects.

Figure 4 shows the effect of wind in a six-hour period, during which there was no precipitation as indicated by the two present weather sensors, the temperature varied within the range of 1.2°C, and the average wind speed was about 5.6 m/s. The precipitation amounts in the three transducers range from about -0.2 to 0.2 mm, with standard deviations of 0.026 to 0.029 mm.

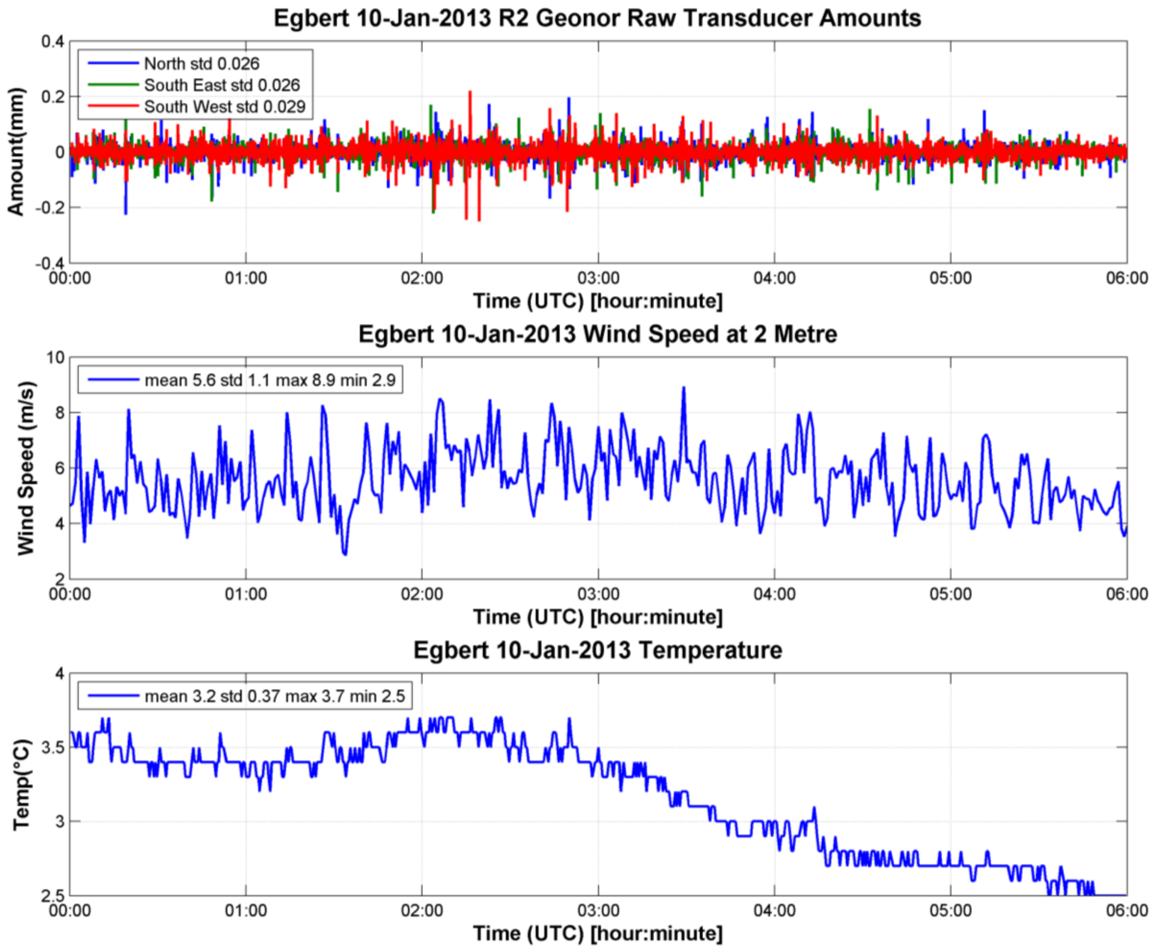


Figure 4: The effect of wind on the R2 transducer precipitation amounts.

The effect of wind on transducer noise can also be seen by plotting the standard deviations of the transducer amounts over periods of no precipitation against the corresponding average wind speeds, as in Section 6.

3.2 Filtering

Besides the max, min and jump filters for removing outliers a moving average filter with a one-minute width (i.e., 10 samples given the sample interval of 6 seconds) is applied to the R2 transducer amounts to remove some of the high frequency noise. The filtered data is backward shifted by a half of the width of the filter (i.e., 5 samples) to compensate for the lag caused by the filtering.

For the data in the first six hours of January 10, 2013, the one-minute moving average filter reduces the standard deviation from about 0.028 mm to about 0.009 mm.

3.3 Gauge Amount

The R2 gauge amount is taken as the average of the three filtered transducer precipitation amounts. Figure 5 and Figure 6 show the filtered precipitation amounts of the three transducers, their average, and the manual observations for the 2012-13 and 2013-14 winters.

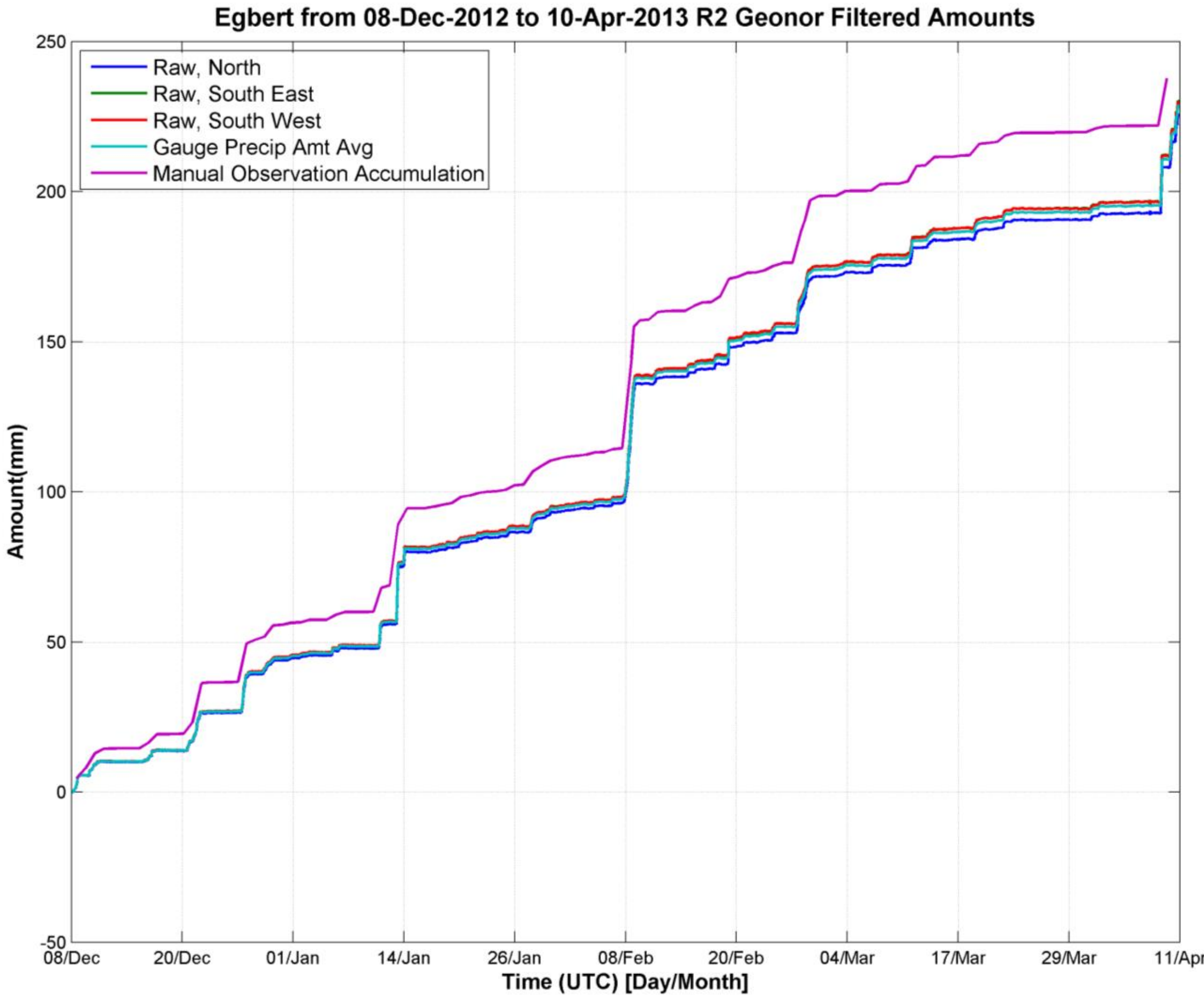


Figure 5: 2012-2013 winter R2 transducer precipitation amounts filtered with a one-minute, moving average filter, their average, and manual observations.

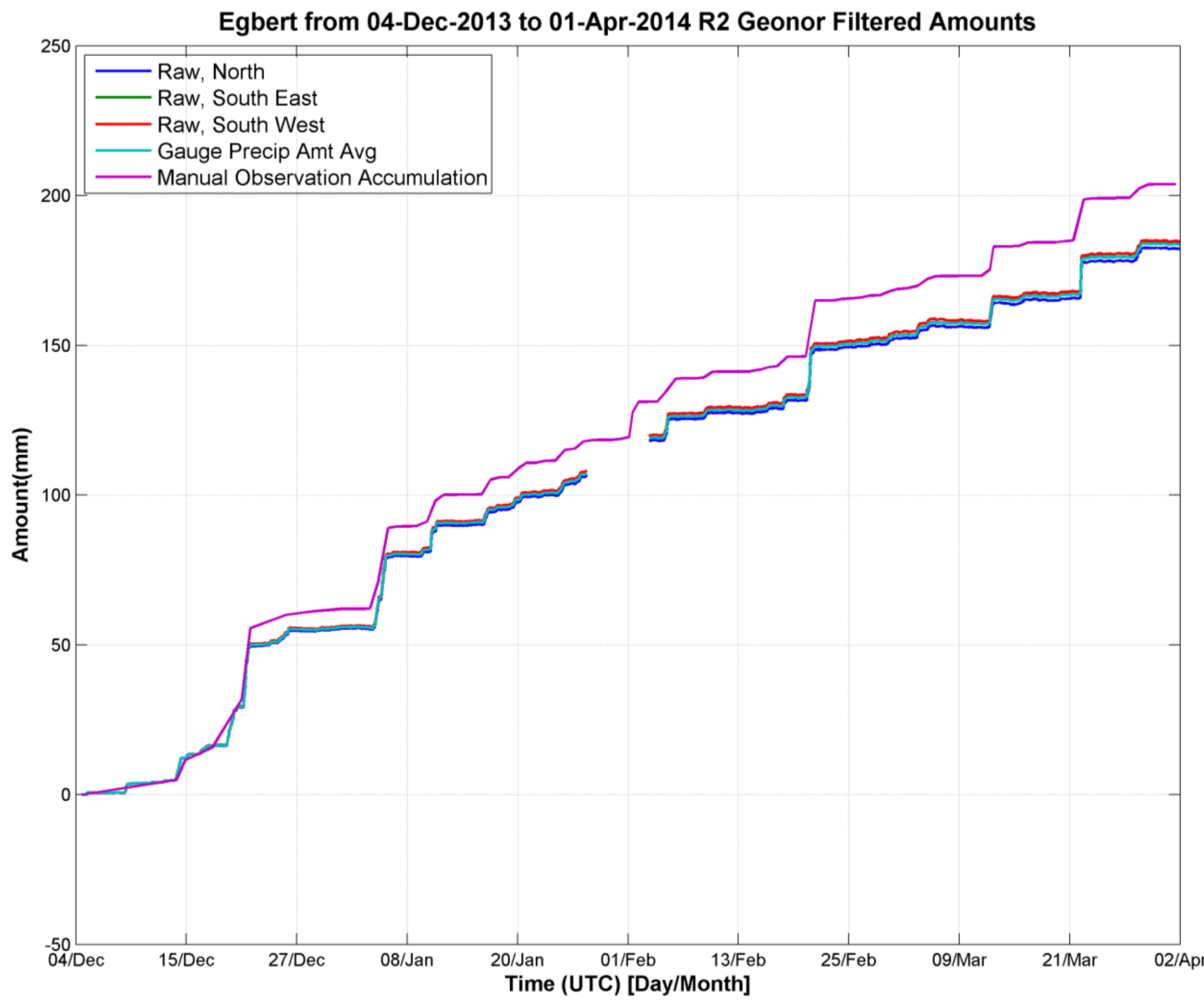


Figure 6: 2013-2014 winter R2 transducer precipitation amounts filtered with a one-minute, moving average filter, their average, and manual observations.

3.4 Temperature Effect

The temperature effect is shown in Figure 7 for a three-day period during which there was no precipitation, the wind speed was on average about 2 m/s and temperature was on average about 3°C and varied over a range of about 14°C. The precipitation amounts in the three transducers varied from about -0.3 to 0.1 mm.

Following [4] the temperature sensitivity coefficient of a transducer can be obtained by plotting the transducer precipitation amount versus temperature. In Section 6 the temperature sensitivity of all the transducers and their average is investigated during periods of no precipitation. The temperature coefficient of the average of the three transducers can vary between -0.11 and -0.24 mm/10°C (see table in Section 7). The average of these temperature coefficients is -0.18 mm/10°C, and the standard deviation is 0.04mm/10°C.

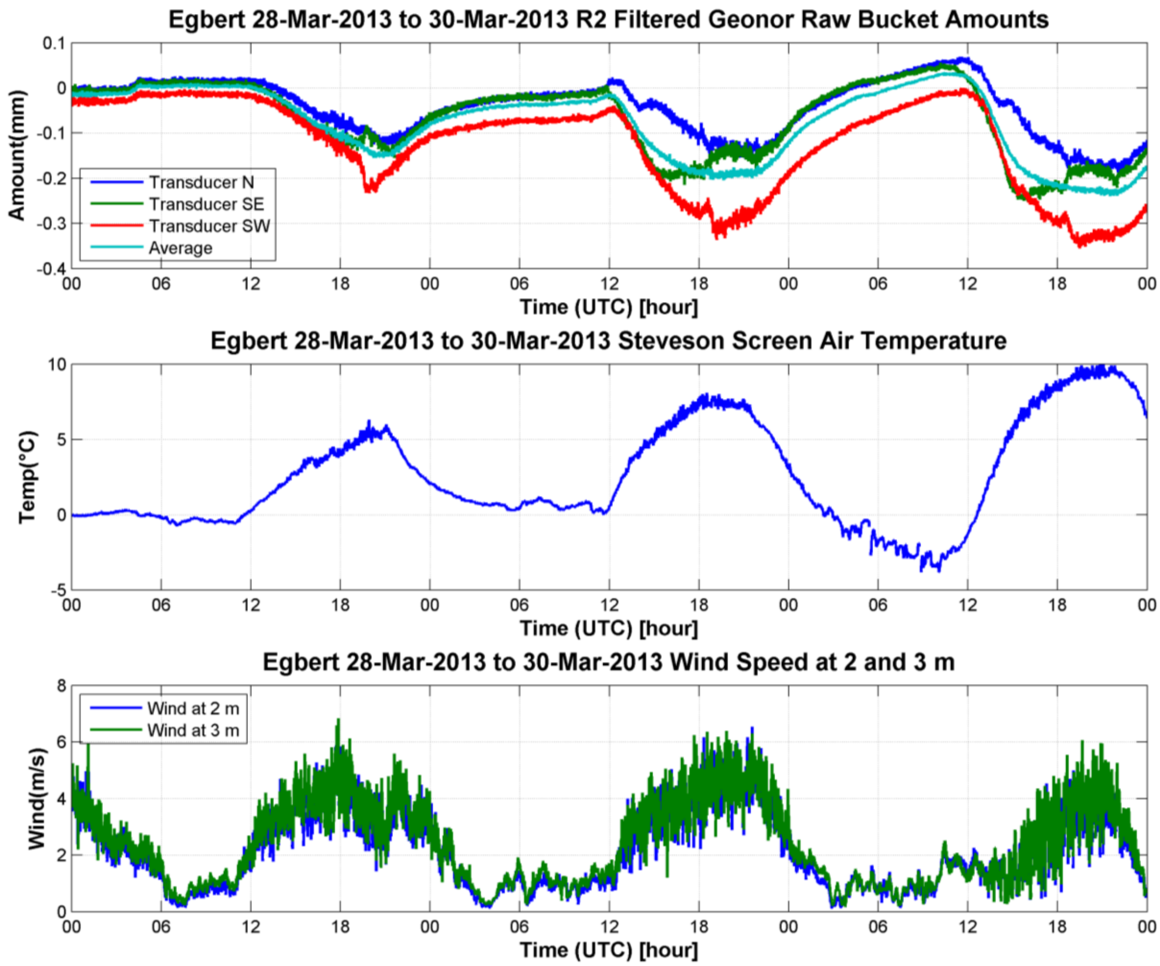


Figure 7: The effect of temperature on the R2 transducer precipitation amounts.

3.5 Noise and Artefact

We next consider the variations in the R2 increments over the manual observation periods during which the R1 increments are less than a specified limit. The R2 increments are plotted in Figure 8 below when R1 increments are less than 0.01 mm (the resolution of the manual observation SWE amount), indicating that there is practically no precipitation. There are 27 such no-precipitation events. The R2 increments, i.e., R2 variations, have an average of -0.056 mm, a standard deviation of 0.098 mm, a maximum of 0.2mm and a minimum of -0.25 mm. To see how these values are affected by the R1 limit, the above analysis is repeated for various R1 limits, and the results are given in Table 1 below. When the R1 limit is greater than 0.3 mm the maximum of the starts to increase, indicating that precipitation is collected in some of the events. The R2 artefact over the manual observation periods has, roughly, a mean within ±0.05 mm, a standard deviation about 0.1 mm and a range of ±0.25 mm.

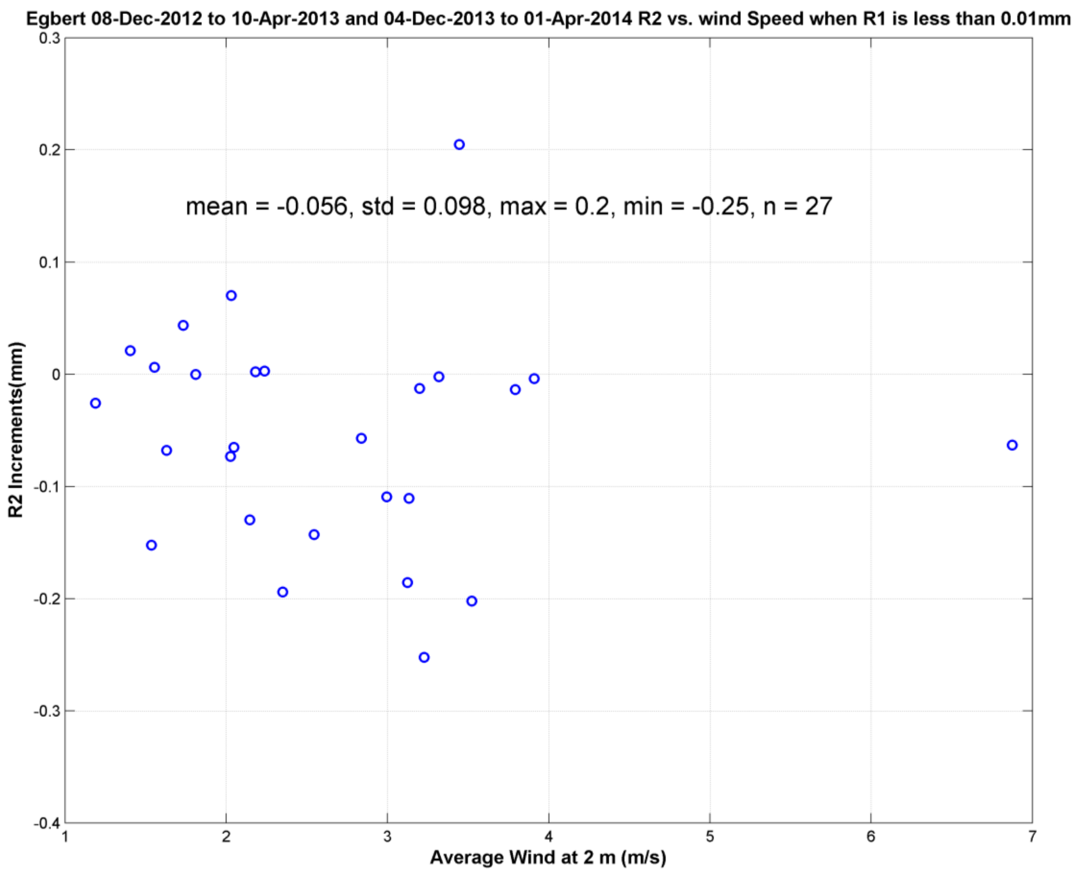


Figure 8: 2012-2013 winter R2 increments over the manual observation periods when R1 is less than 0.01 mm.

R1 Increment Limit (mm)	Number of Events	R2 Increments			
		Mean (mm)	St. Dev. (mm)	Max (mm)	Min (mm)
0.01	27	-0.056	0.098	0.2	-0.25
0.05	64	-0.027	0.098	0.2	-0.25
0.1	86	-0.011	0.098	0.2	-0.25
0.2	99	0.003	0.1	0.23	-0.25
0.3	105	0.016	0.12	0.37	-0.25
0.4	110	0.031	0.13	0.38	-0.25
0.5	117	0.058	0.17	0.58	-0.25

Table 1: 2012-2013 and 2013-2014 winter R2 increments for various R1 limits.

3.6 Solid Precipitation

Following the approach in [11] and [12] we select those events whose maximum temperature over the observation period is less than -2°C as solid precipitation events.

3.7 Catch Efficiency

3.7.1 Catch Efficiency versus Wind Speed

The influence of wind speed on the CE is analyzed. Figure 9 shows a plot of CE vs. wind speed when both increments are greater than 1 mm, a limit that is also used in [11], and Figure 10 shows a scatter plot of

R2 vs. R1 increments. There are 25 events over the winters of 2012-13 (with 10 events) and 2013-14 (with 15 events) with the accumulation greater than the 1 mm limit. The data is given in Table 2 below.

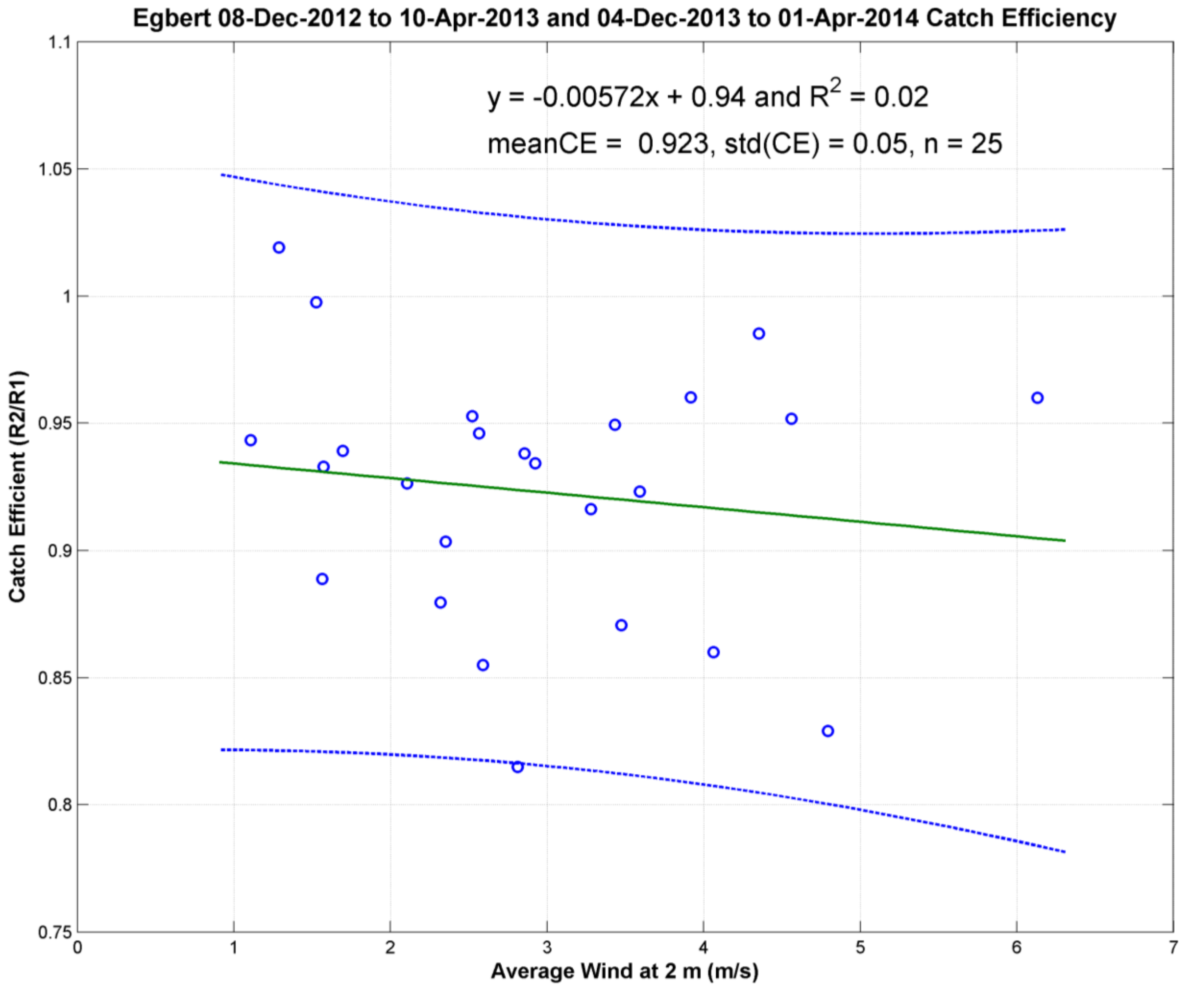


Figure 9: Catch Efficiency vs. wind Speed for events with 1 mm or more accumulations. The green line is the linear regression with the equation and R^2 given in the figure, and the blue dotted lines indicate the 95% prediction levels. The mean and standard deviation of the CE are also included.

We test whether the slope of linear regression in Figure 9 is significantly different from zero at 95% confidence level, and the test result shows that the slope is not significantly different from zero.

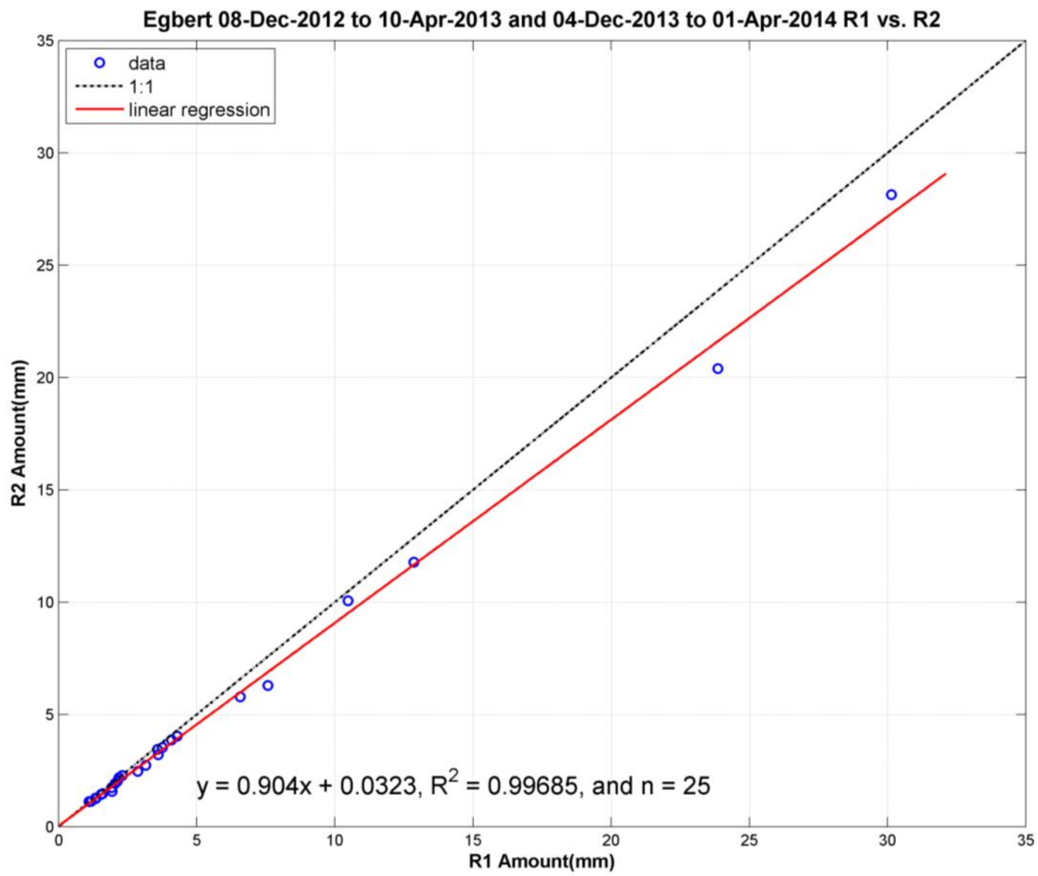


Figure 10: scatter plot of R2 vs. R1 when both increments are greater than 1 mm.

We test whether the slope of linear regression in Figure 10 is significantly different from one. The test result shows that the slope of 0.904 is different from 1 at the 5% significant level.

Start Date Time	End Date Time	R1 Inc (mm)	R2 Inc (mm)	CE	R1-R2 (mm)	Max T (°C)	Avg. Wd (m/s)
26/12/2012 15:35	27/12/2012 14:11	12.86	11.78	0.916	1.08	-5.4	3.3
27/12/2012 14:11	28/12/2012 13:43	1.19	1.13	0.953	0.05	-5.2	2.5
29/12/2012 14:19	30/12/2012 14:05	3.76	3.53	0.938	0.23	-4.2	2.9
25/01/2013 13:42	26/01/2013 13:40	1.54	1.44	0.933	0.10	-9.7	1.6
07/02/2013 15:13	08/02/2013 15:50	30.13	28.15	0.934	1.99	-6.0	2.9
08/02/2013 15:50	08/02/2013 22:39	10.47	10.05	0.960	0.42	-9.6	3.9
08/02/2013 22:39	09/02/2013 15:30	2.13	2.02	0.949	0.11	-10.2	3.4
17/02/2013 13:40	18/02/2013 14:05	1.93	1.57	0.815	0.36	-11.7	2.8
20/02/2013 13:17	21/02/2013 13:57	1.34	1.28	0.952	0.06	-7.2	4.6
03/03/2013 13:09	04/03/2013 15:05	1.6	1.48	0.925	0.12	-6.3	3.6
14/12/2013 20.56	15/12/2013 18:48	6.58	5.79	0.879	0.79	-7.2	2.3
15/12/2013 18:48	18/12/2013 17:00	4.29	4.03	0.939	0.26	-2.2	1.7
21/12/2013 20:25	22/12/2013 19:20	23.86	20.40	0.855	3.46	-2.3	2.6

19/01/2014 15:18	20/01/2014 15:24	2.86	2.46	0.860	0.40	-2.1	4.1
20/01/2014 15:24	21/01/2014 13:29	1.92	1.73	0.903	0.19	-13.1	2.4
24/01/2014 15:31	25/01/2014 16:05	3.58	3.44	0.960	0.14	-5.5	6.1
26/01/2014 19:45	27/01/2014 16:09	2.31	2.28	0.985	0.03	-6.7	4.4
04/02/2014 15:31	05/02/2014 15:47	3.6	3.20	0.889	0.40	-6.1	1.6
05/02/2014 15:47	06/02/2014 15:52	4.09	3.87	0.946	0.22	-8.2	2.6
09/02/2014 14:50	10/02/2014 15:28	2.04	1.92	0.943	0.12	-9.3	1.1
17/02/2014 14:55	18/02/2014 15:28	3.15	2.74	0.871	0.41	-2.3	3.5
28/02/2014 15:46	01/03/2014 15:37	1.35	1.25	0.926	0.10	-7.7	2.1
04/03/2014 15:45	05/03/2014 16:29	2.18	2.17	0.998	0.01	-9.2	1.5
05/03/2014 16:29	06/03/2014 15:50	1.1	1.12	1.019	-0.02	-7.7	1.3
12/03.2014 12:16	12/03/2014 21:18	7.58	6.28	0.829	1.30	-2.2	4.8
R1, R2 Sum (mm)		137.44	125.11				

Table 2: The R1 and R2 increments used in Figure 9, along with observation time, maximum temperature and average wind speed.

The difference of R1 and R2 are plotted against in Figure 11 below.

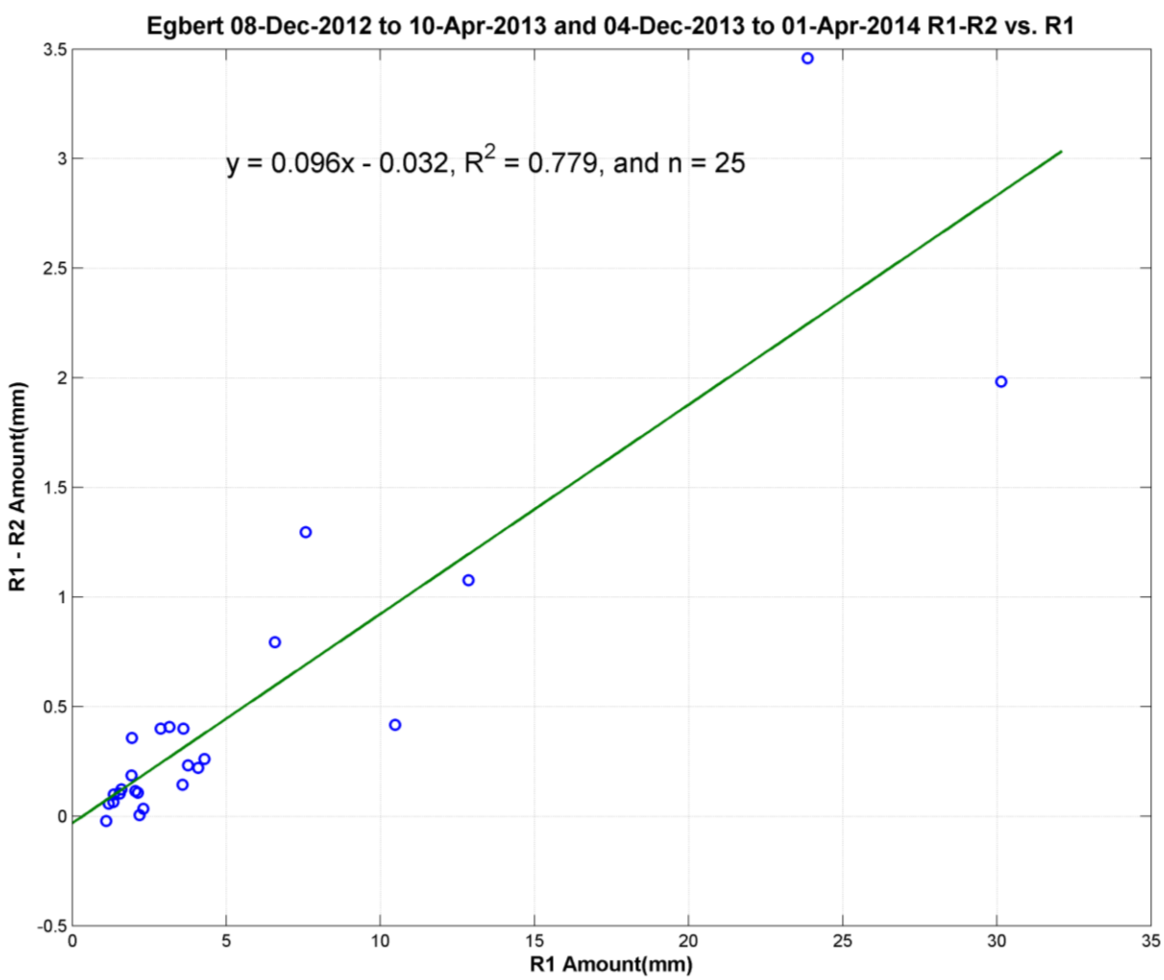


Figure 11: The difference of R1 – R2 vs. R1 increments.

3.7.2 Temperature Effect on R2

We note that in Figure 9 there is one point that lies close to 80%, and that with reference to Table 2 this point corresponds to the observations on February 17 and 18, 2013. By examining the time series plots for February 17 and 18, 2013 in Section 8, we see that there is a variation in the gauge amount in response to the variation in the ambient air temperature.

The effect of temperature on the R2 measurement can be compensated as follows:

$$AdjustedEventAmount = m_2 - m_1 - \frac{\alpha(T_2 - T_1)}{10}$$

where m_1 and m_2 are the measurements of the R2 gauge amounts in units of mm, T_1 and T_2 are the air temperature in units of degree Celsius, at the start and end of the event respectively, and α be the temperature coefficient in units of mm/10°C. For Geonor α is negative.

For Geonor the transducer temperature is not available, thus air temperature is used instead. We note that there could be a substantial difference between the air temperature and transducer temperature, and that this could be another source of uncertainty.

We consider the adjustment for temperature effect for the event (17/02/2013 13:40, 18/02/2013 14:05).

The gauge amount at 13:40 on the 17th and 14:05 on the 18th are respectively 0.23mm and 1.80 mm. The air temperatures at these times are respectively -17.7°C and -12.7°C. The adjusted amount is 1.66mm, using -0.18mm/10°C.

In Section 8 the other events in Table 2 are adjusted for the effect of temperature.

The plot of the adjusted CE versus average wind speed is shown in Figure 12.

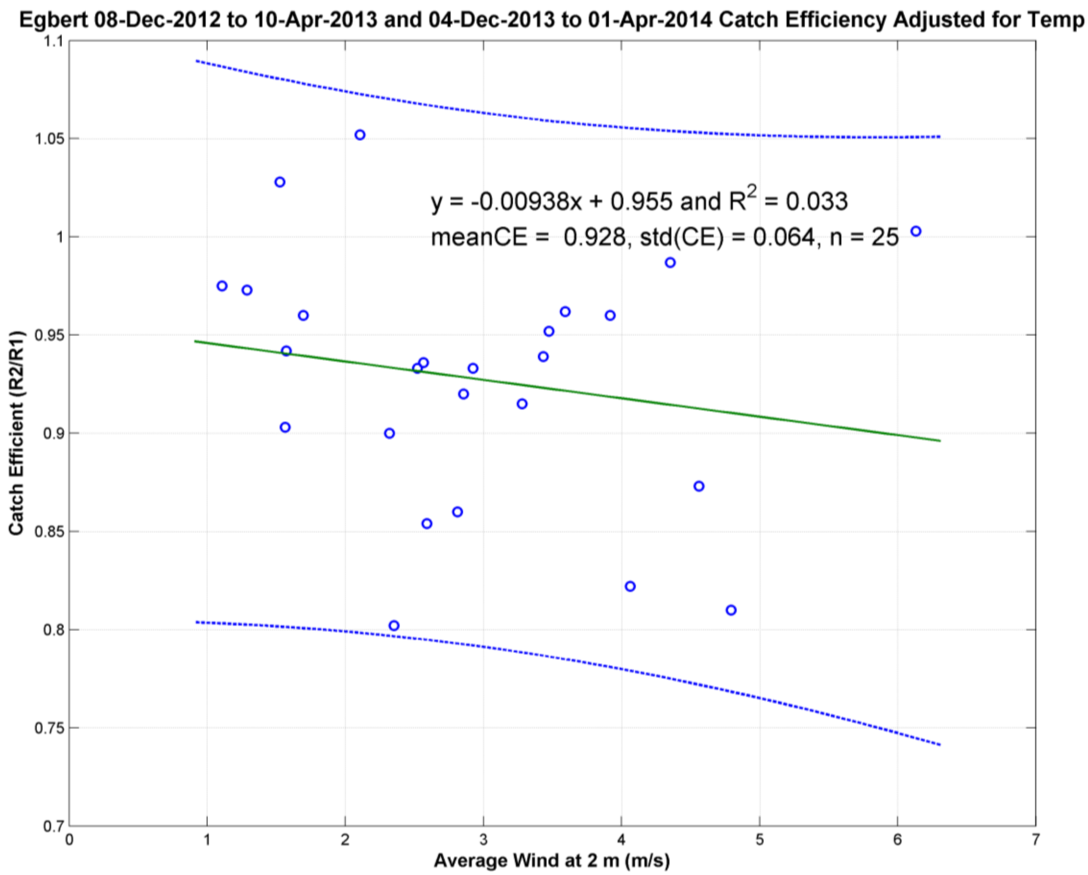


Figure 12: Catch Efficiency adjusted for temperature effect vs. wind Speed for events with 1 mm or more accumulations.

The mean of the CE with type 2 adjustment is slightly larger than that in Figure 9, and the standard deviation of the adjusted CE is also larger.

The slope of the adjustment is not significantly difference from zero at the 95% confidence level.

3.7.3 Frost on R1

Frost can form on the inside as well as the outside wall of the R1 collector. It was noted by the manual observer that “frost played a part in the collection” and that “the frost was heaviest on the outside of the collector, followed by the upper third of the inside; while the bottom 2/3 were relatively clean.”[2] The outside frost, and any adhered precipitation, is removed before the gauge is weighed ([5]).

On February 10, 2013 the observer noted that the collector was covered with frost both on the outside and, to a lesser extent, inside. After cleaning the outside the collector weighed 1641.6 g. With the inside also cleaned down to, and including, the partial fin, the collector weighed 1638.6 g. There was limited frost below the fin to the bottom of the collector. The empty collector weighs 1638.3 g. A picture of the R1 manual gauge with frost is shown in Figure 13.

[2] See P. Raczynski’s Blog in cspice.ca.

Figure 13: Frost on the R1 manual gauge (courtesy of P. Raczynski).

The observed noted that it was clear and sunny the day before, and that there was a morning fog on February 10. The weather reports from PWD22 and Parsivel on February 9 and 10 are shown in Section 10. There was no precipitation reported from Parsivel between the observation times of 2013 February 9 15:30 and February 10 13:58. There was some light snow reported by PWD22 at 13:05:07 but with no accumulation. At about the same time, PWD22 also reported mist and freezing fog in its METAR, which lasted until 14:12:06. Visibility reduced to about 700 metres during the freezing fog.

It was strongly suspected that the increase in the collector weight was due to the frost resulted from the fog. In this case the accumulation is 0.05 mm/g × (1641.6 g – 1638.3 g) = 0.16 mm.

During the winter of 2012-2013 frost was reported in nine of the observations, and during the winter of 2013-2014 six frost events are reported.

For the twenty five events in Table 2 frost was reported in the observation for the event (25/1/2013 13:42, 26/1/2013 13:40) and event (17/02/2013 13:40, 18/02/2013 14:05).

For the former event the weight of the collector, with the outside cleaned, was 1669.1 g. After the upper section of the inside was cleaned the collector weighed 1667.7 g. The collector weighed 1638.8 g after the removal of the snow, and it weighed 1638.5 g after the cleaning of the bottom two thirds of the inside. Assuming the frost formed mainly in the upper section of the inside, as observed above, the weight of the precipitation, removing the weight of frost, was 1667.7 g – 1638.3 g (weight of the empty collector) = 29.4 g, which is 1.47 mm of precipitation, instead of the 1.54 mm when the inside frost was not removed. The adjusted CE is then 1.44/1.54 = 98.0%. The CE before this adjustment is 93.5%.

For the latter event, with the upper one thirds of the inside cleaned the weight was 1676.4 g, and this resulted in a precipitation amount of 1.91 mm. The adjusted CE is 91.1%.

The CE adjusted for both temperature and frost are summarized tables provided in Section 9.

The plot of the CE adjusted for temperature effect and frost versus average wind speed is shown in Figure 14.

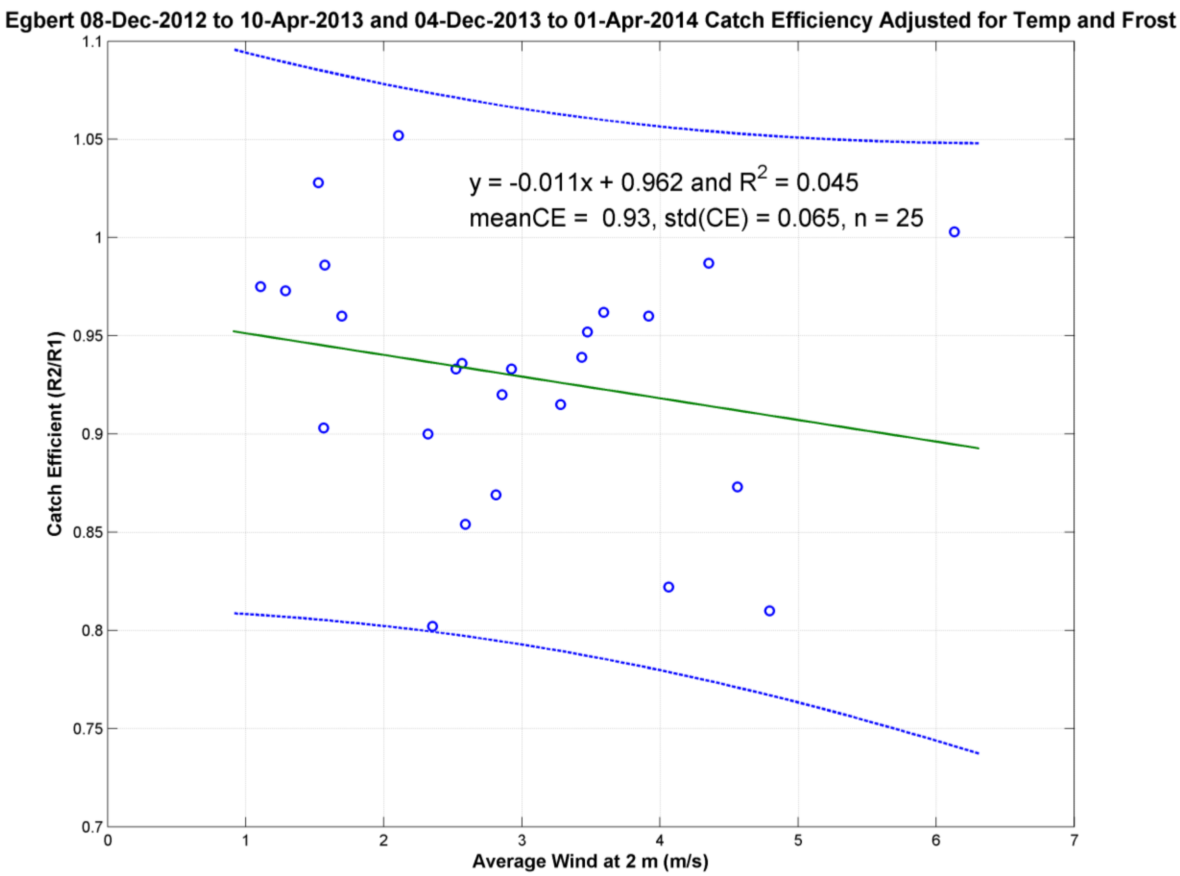


Figure 14: Catch Efficiency (adjusted for temperature effect and frost) vs. wind Speed for events with 1 mm or more accumulations.

The slope of Figure 14 is not significantly difference from zero at the 95% confidence level.

It is possible that snow could adhere to the frost on the inside of the collector. Thus, adjusting for frost on the R1 measurements could introduce another source of uncertainty.

3.7.4 Different R1-R2 Limits, Temperature Limits and Moving Average Widths

We vary the limit for R1 and R2 but keep the temperature limit for solid precipitation at -2°C. The effects of different limits on the average CE and other parameters are given in Section 10.

Keeping the R1-R2 limit at 1 mm we vary the temperature limit for precipitation. The effects of this variation on the temperature limit are given in Section 10.

Keeping the R1-R2 limit at 1 mm and the temperature limit for solid precipitation at -2°C we vary the moving average filter width. The effects of this variation are given in Section 10.

3.8 Difference of about 7% of R2 with respect to R1

We note from Figure 9 that there is a difference of about 7% of R2 with respect to R1. We will look into some possible causes of this offset.

3.8.1 R1

In a long-term intercomparison of 6 Tretyakov gauges ([13]) the mean catch ratios for snow are, relative to one of Tretyakov gauges, 94% to 106%. Thus, the uncertainty in the Tretyakov gauges would more or less account for this difference, assuming that R2 is accurate.

Nevertheless we will look at R1 in some details in the hope of a better understanding of the causes of this difference. R1 has a laboratory uncertainty of 0.01 mm, as discussed above. The scale was calibrated in January, 2012 and in July, 2013 with calibration error less than 0.01 mm in either case.

Recall that in computing the SWE from the weight of the precipitation collected the collecting area is assumed to be 200 cm^2. We now consider how much the radius of the R1 collecting area needs to be changed to produce a difference of 7%, assuming that R1 and R2 are the same if there were no error in the collecting area of R1. The precipitation amount h is related to the weight as follows:

$$h = \frac{\Delta m}{\rho A} = \frac{\Delta m}{\rho \pi r^2}$$

where Δm is the weight of the precipitation collected, ρ is the density of water, assuming to be 1000 kg/m^3, A is the collecting area with r its radius. If the actual collecting area is larger than 200 cm^2, but the calculation is made using 200 cm^2 as the collecting area, the depth of precipitation will be larger. Consider

$$\frac{h_1}{h_2} = \frac{\Delta m}{\rho \pi r_1^2} \frac{\rho \pi r_2^2}{\Delta m} = \left(\frac{r_2}{r_1}\right)^2 = 0.93$$

Thus, $r_1 = r_2 / \sqrt{0.93}$. For the collecting area that is exactly 200 cm^2, r_0 is 79.788 mm and this is used in the calculation. To get the 1/0.93 increase in depth precipitation, the actual radius needs to be $r_0 / \sqrt{0.93}$, and this implies a difference of $r_0 / \sqrt{0.93} - r_0 = (1 - \sqrt{0.93}) r_0 / \sqrt{0.93} = 2.95 mm$. It seems unlikely that there is an error of this magnitude, about 3.7% of r_0, in the radius. A measurement of one of the collectors shows that its radius is within 0.4 mm of r_0. Thus, the uncertainty in the collecting area might contribute to the offset, but it alone is unlikely to account for the full 7% difference.

A constant density of water of 1 g/cm^3 is used in the calculation of the SWE. Judging from the Section 5.4 of [6] of checking the function of the transducer, it appears that the same constant density of water is also used by Geonor.

The calibration of the scale had been verified. The error in the calculation of the R1 amounts due to the uncertainty of the collecting area, if any, is unlikely to be the cause of this difference.

3.8.2 R2

The R2 Geonor gauge was assessed in a field verification in July 2013 ([8]). In this field verification water of approximately 1 kg, corresponding to 50 mm of precipitation, was added, in 12 successions, to the empty Geonor bucket, thus covering the full range of the Gauge capacity of 600 mm. For each of the 13 weights (including the empty bucket) the frequency of each transducer was recorded. For each transducer, the new empty bucket frequency f_0 is obtained from the empty bucket measurement, and a least squares fit is used to generate the coefficients A and B.

The results of the R2 Geonor calibration are given in Table 12 of [8]. The errors between the gauge amount (i.e., the average of the three transducer amounts) and the reference amount generated by water weighed to roughly 1 kg (i.e., 50 mm in depth) have a maximum of 0.15 mm, a minimum of -0.14 mm, an average of 0.03 mm, and a median of 0.01 mm. The percentage errors between the gauge amount and the reference amount have a maximum of 0.29%, a minimum of -0.28%, an average of 0.06%, and a median of 0.02%.

Thus, the calibration of R2 Geonor is probably not the cause of this difference.

3.8.3 Measurement and Heating of the R2 Gauge

We now consider the structure of the R2 Geonor gauge and how it might contribute to the 7% difference. Below in Figure 15 is a schematic of the Geonor gauge, taken from [6]. The inlet orifice is a long tube, hanging above the weighing bucket. In the passage through this inlet orifice, it is conceivable that some of the precipitation adheres to the inner wall of the inlet orifice, and does not enter into the bucket below, thus will not be weighted. For liquid precipitation it is almost certain that there will be some wetting loss on the inner wall. Snow can also adhere to the inner wall of the orifice. When this happens the adhered snow will probably not be weighed for the current manual observation period. Heating, both at the top and bottom, of the inlet orifice could contribute to the evaporation of any precipitation adheres to the orifice wall.

On the other hand any precipitation that adheres to the inner wall of the manual gauge will also be weighed, as the whole gauge, after removing any precipitation adheres to the outside wall of the gauge, is weighed, assuming that no adjustment for frost is made.

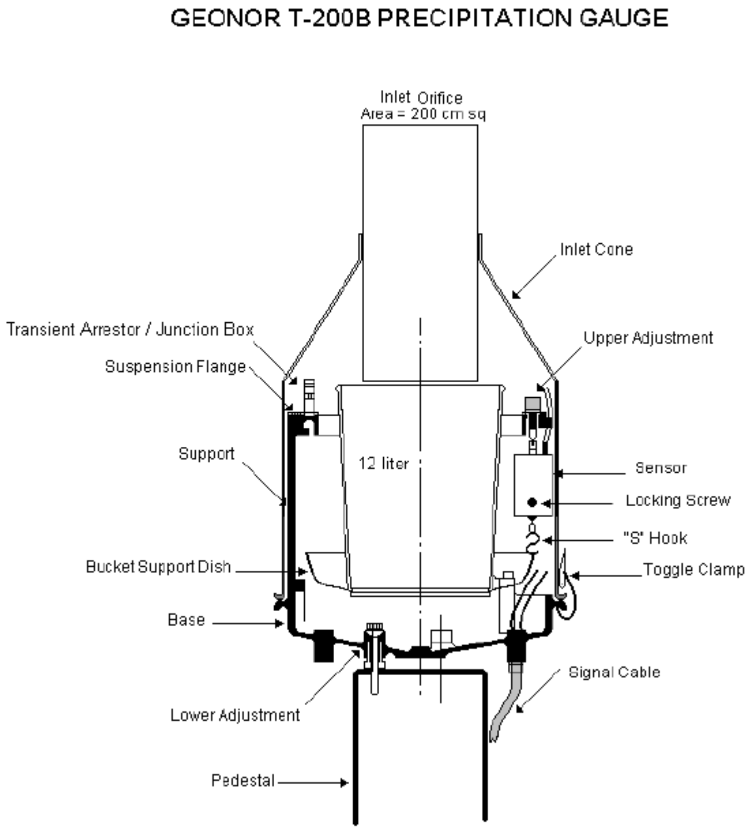


Figure 15: A schematic of the Geonor gauge (from [6]).

In tests conducted at the NCAR Foothills laboratory ([3]) Geonor T200B3 shows an underestimation when the snowfall rates are very low and the heater is active. It is also observed in [3] that the large inner surface of the heated orifice of the Geonor T200B3 could be responsible for the retention and evaporation of the melted snowflakes stuck to the walls when the snowfall rate is low.

The R2 Geonor orifice is equipped with upper and lower heater in the USCRN manner ([1]). The differences between the R1 and R2 increments (both greater than 1 mm) are plotted against the percentage of time when the upper rim heater is on (Figure 16), and against the percentage of time when the rim temperature (the average of the upper and lower rim temperature) is above the ambient air temperature by 1°C or more (Figure 17). The plots seem to show that there are generally larger differences when the upper rim heater is on more often, and when the rim temperature is above the ambient air temperature more often.

Figure 18 shows a plot of the differences between R1 and R2 increments (both greater than 1 mm) against the maximum temperature of the events. It seems to show that the larger differences appear to occur when the maximum ambient air temperatures of the events are between -5°C and 5°C. We note also that according to the heating logic in [1] the upper/lower heater is turned when the ambient air temperature is between -5°C and 5°C and upper/lower rim temperature is below 2°C.

When examining weather reports of all the differences greater than 1 mm, all except two show some form of mixed precipitation, with the largest difference (at 3.46 mm) showing freezing rain (Figure 19).

All these seem to suggest that rim heating and precipitation freezing on the inlet orifice could be some of the causes of this deficiency.

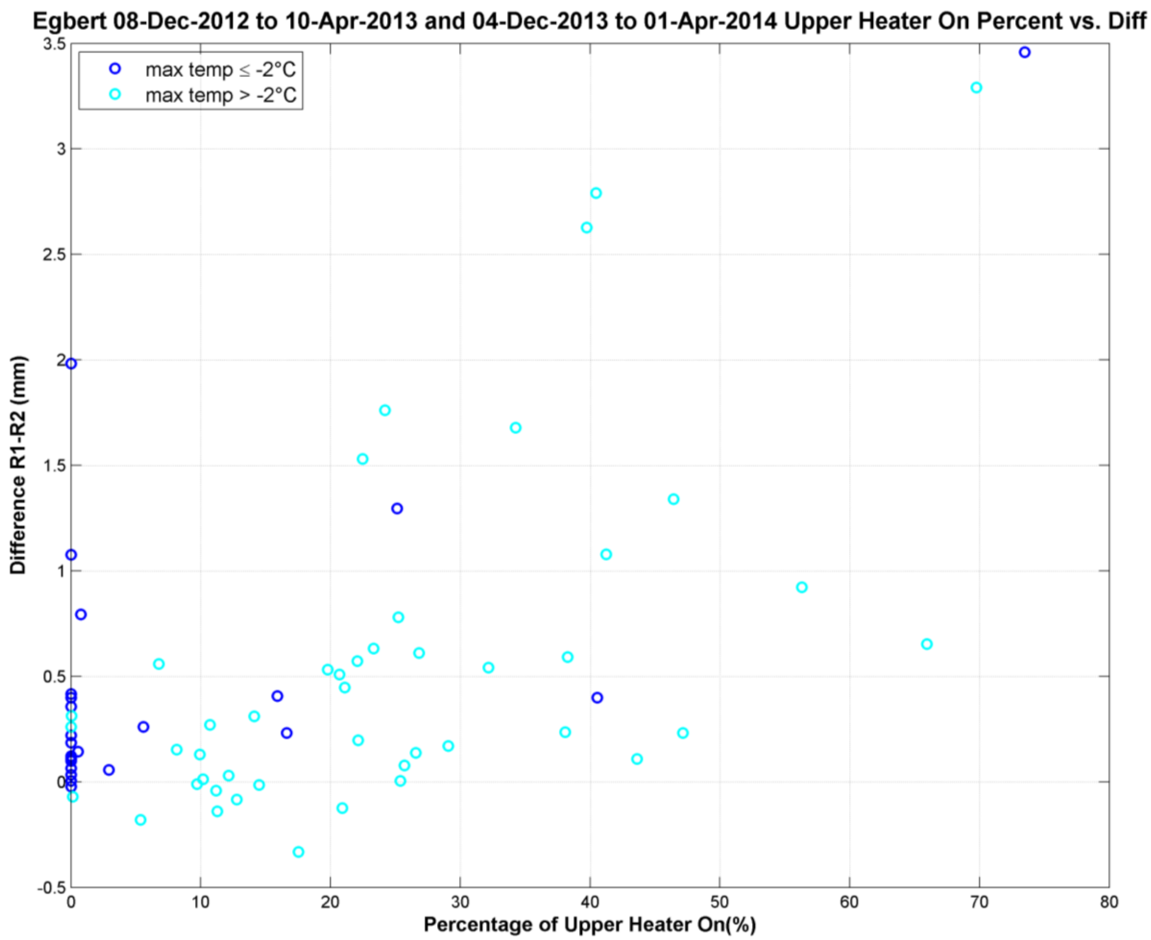


Figure 16: A plot of the percentage of time when the upper rim heater is on vs. differences between R1 and R2 amounts, with both amounts greater than 1 mm but no temperature limit.

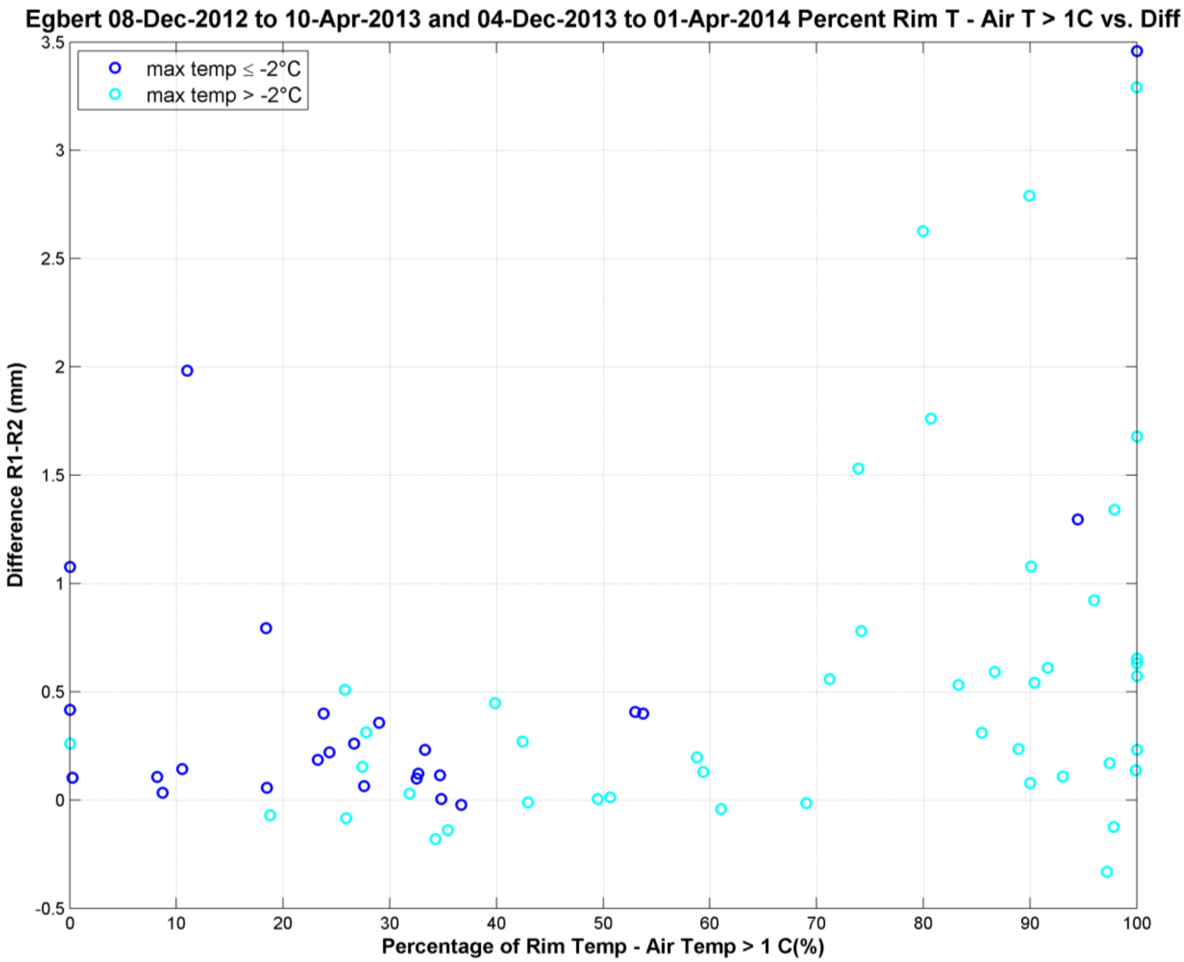


Figure 17: A plot of the percentage of time when the rim temperature is more than 1°C warmer than the air temperature vs. differences between R1 and R2 amounts, with both amounts greater than 1 mm but no temperature limit.

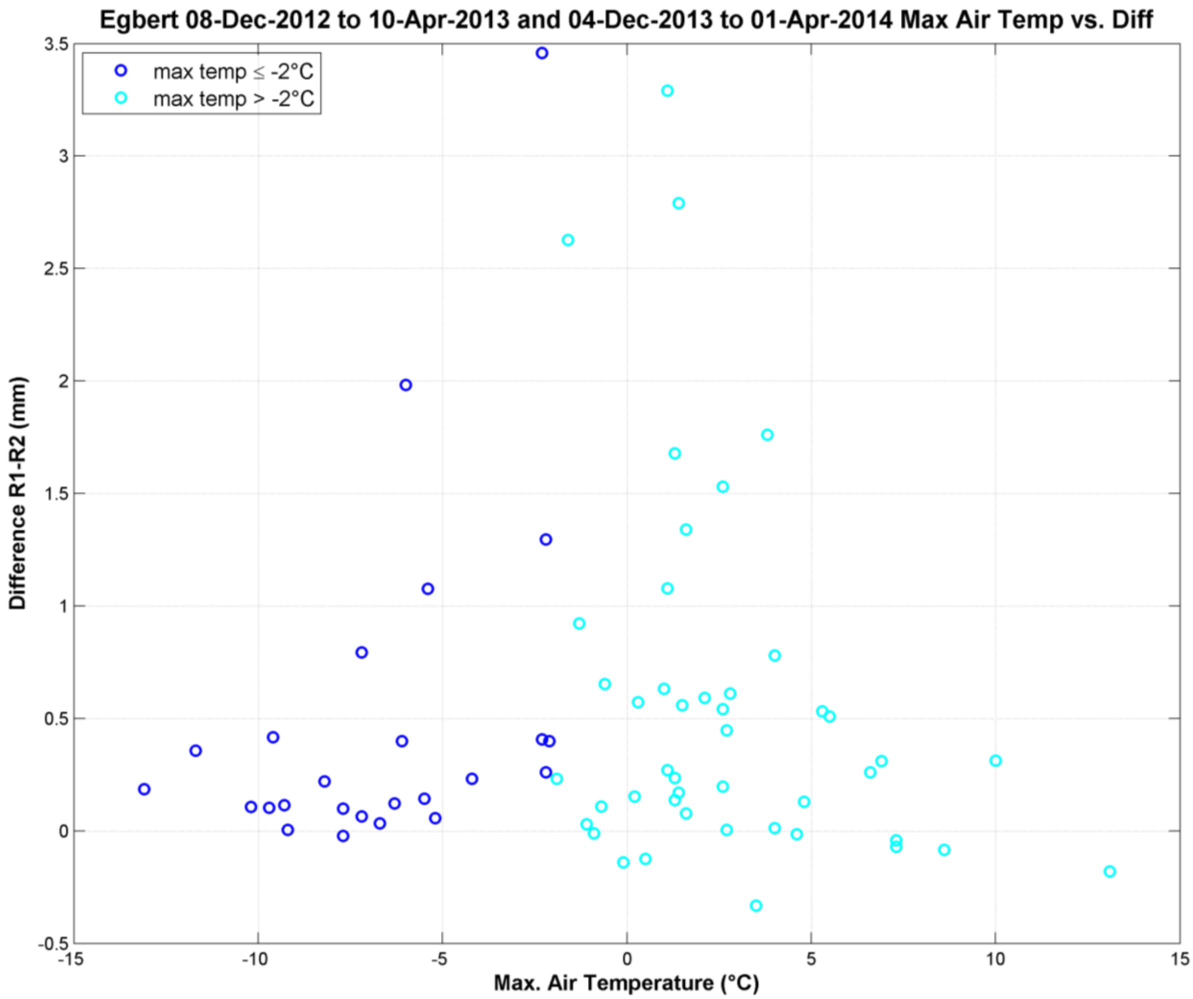


Figure 18: A plot of the maximum ambient air temperature of the events vs. differences between R1 and R2 amounts, with both amounts greater than 1 mm but no temperature limit.

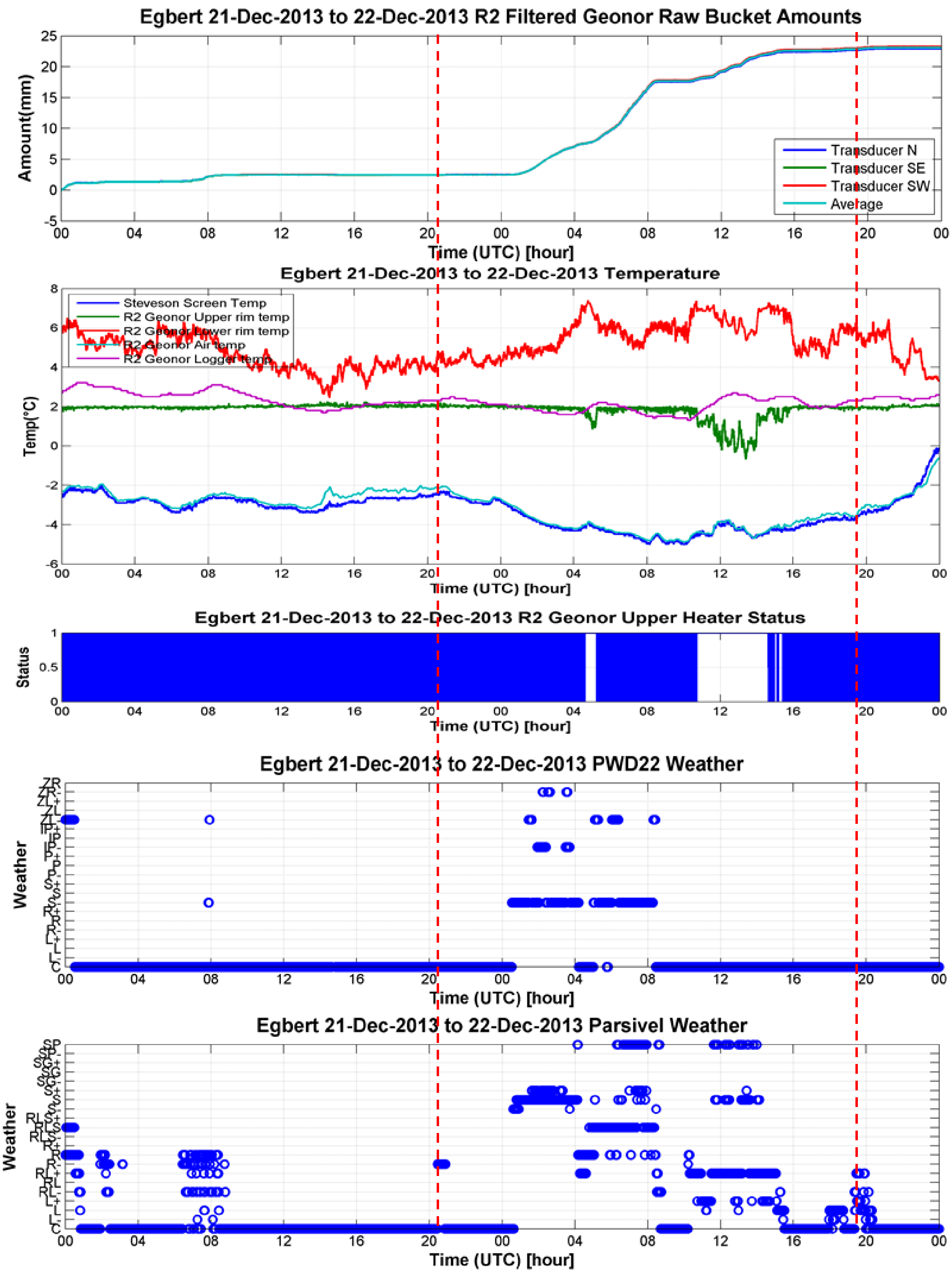


Figure 19: Precipitation amounts, temperatures, upper heater status, and weather reports for the event 2013 December 21 to 22, which has the largest difference of R1 – R2, at 3.46 mm.

For the coming winters it would be useful to make an observation of the R2 Geonor to see if snow adheres to the inner wall of the inlet orifice when making a manual observation on R1.

4 Summary

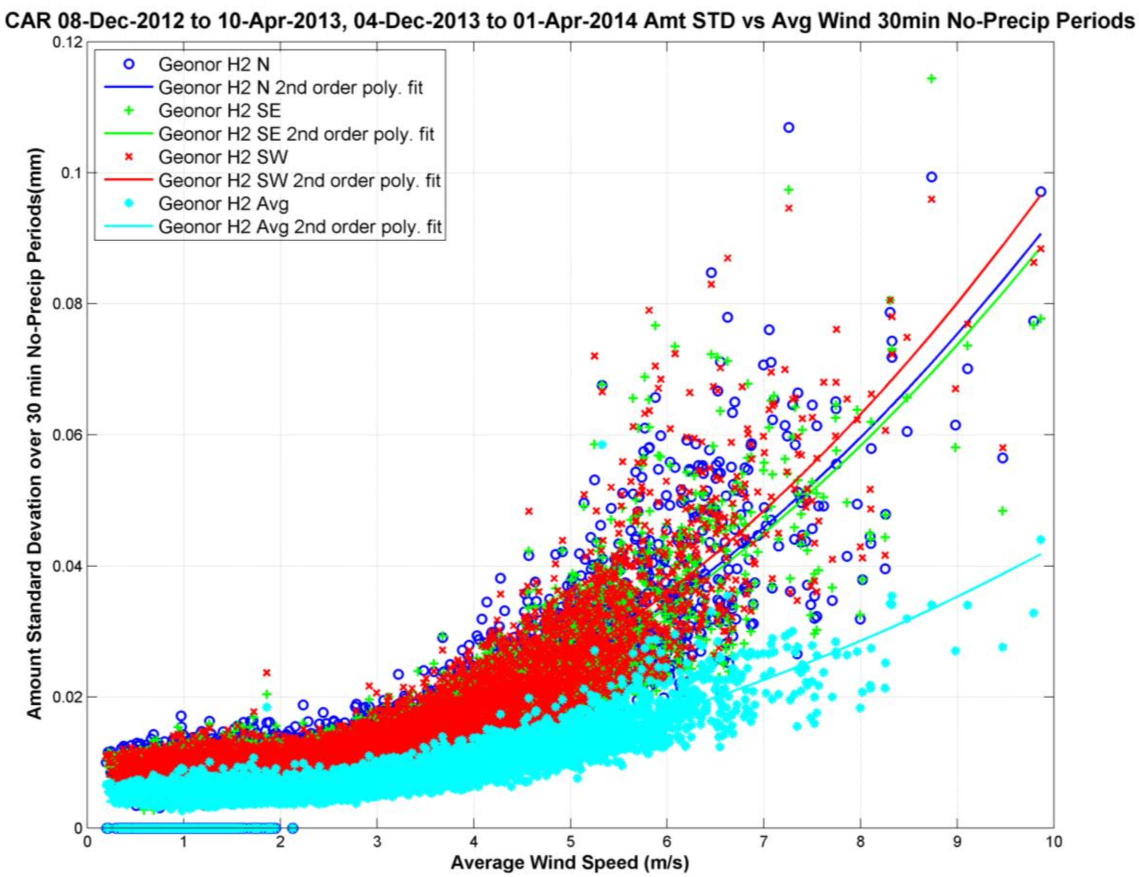
We analyze the data from a manual Tretyakov gauge (R1) and a Geonor T-200B3 automatic gauge (R2) both inside DFIR double fences in the CARE site for the 2012-13 and 2013-14 winters. The analysis shows that the dependence of the catch efficiency (R2/R1) on the wind speed is not “strong” for the range of 1 to 6 m/s, and that the automatic gauge (R2) catches about 7% less than the manual gauge (R1). We verify the calibration of the scale for weighing the precipitation from the manual gauge and the transducers of the Geonor gauge, and speculate on some of the factors that might cause the difference between the manual and automatic gauges.

5 Acknowledgements

The authors would like to thank Craig Smith, Roy Rasmussen, Mareile Wolff, and Daqing Yang for their comments and suggestions to this work.

6 Appendix A – Wind Effect

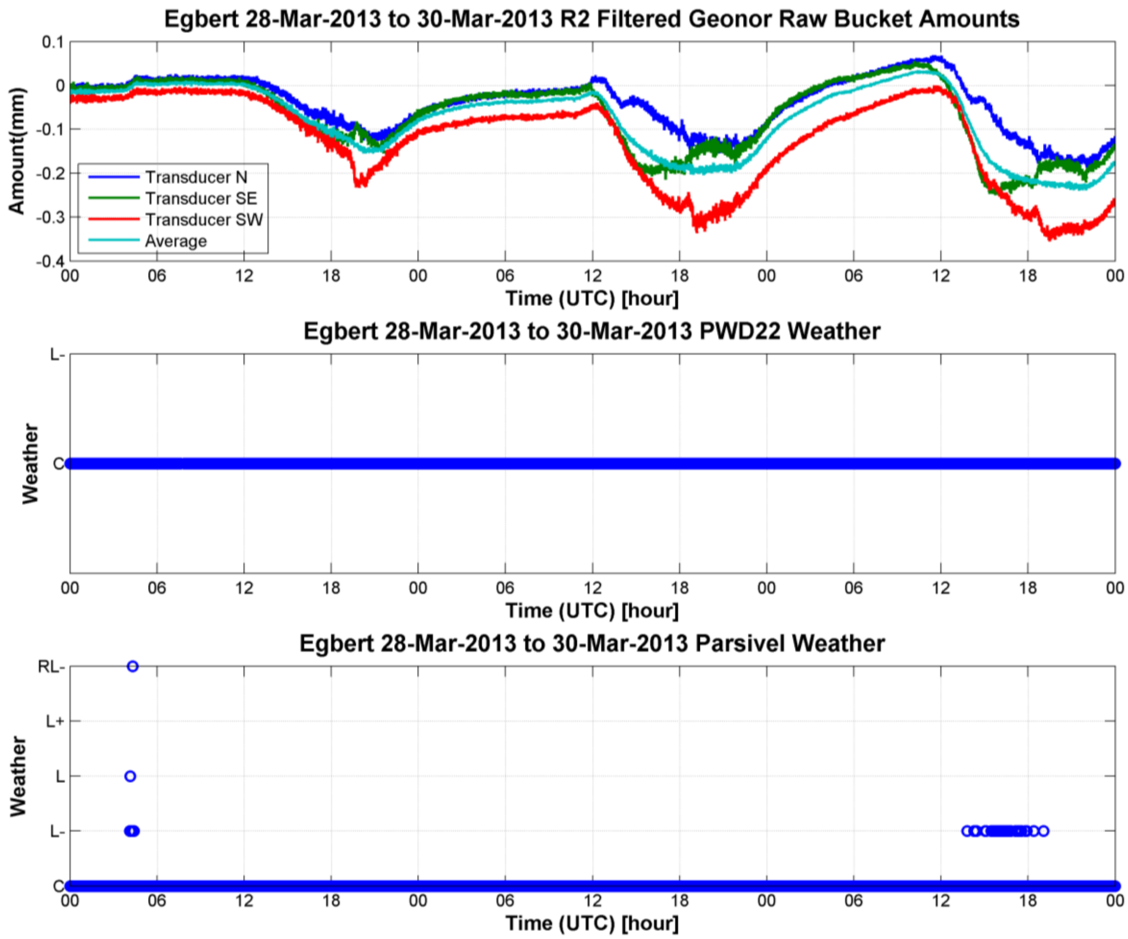
The effect of wind on the transducer noise can be seen by plotting the standard deviations of the transducer amounts and gauge amounts over 30 minute periods of no precipitation (according to PWD22 and Parsivel) against the average wind speeds over the corresponding 30 minute periods, as shown below.



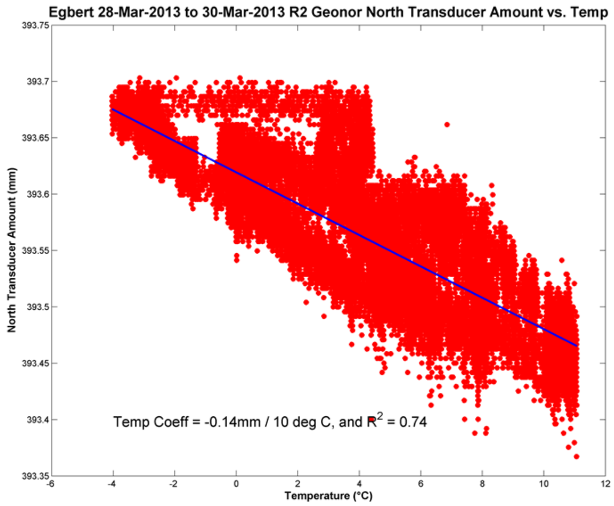
7 Appendix B – Transducer Temperature Sensitivity

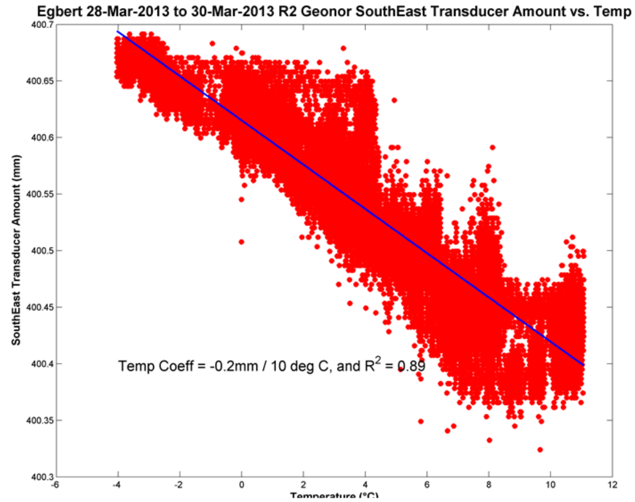
In this appendix the temperature sensitivity of all the transducers and their average is investigated during periods of no precipitation.

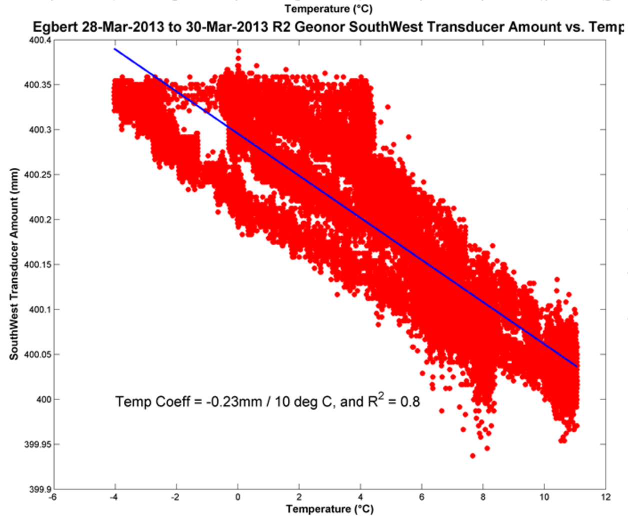
As an example, the period from Mar 28 to 30, 2013 is considered. The transducer amounts, air temperature, wind speed, and present weather reports for this period are given in Figure 7 and below. Parsivel reported some drizzle, mostly light, on March 28 and 30, but the total accumulation of these reports is only 0.03 mm, less than the resolution of the Geonor gauge.

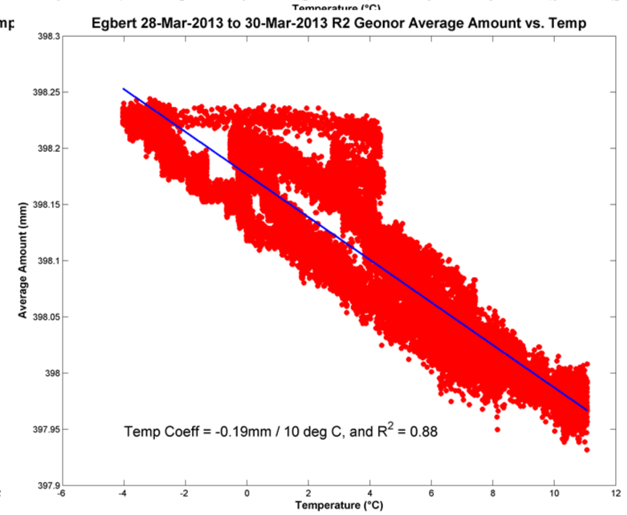


The temperature sensitivity coefficients for the transducers and their average for these three day period are given below.







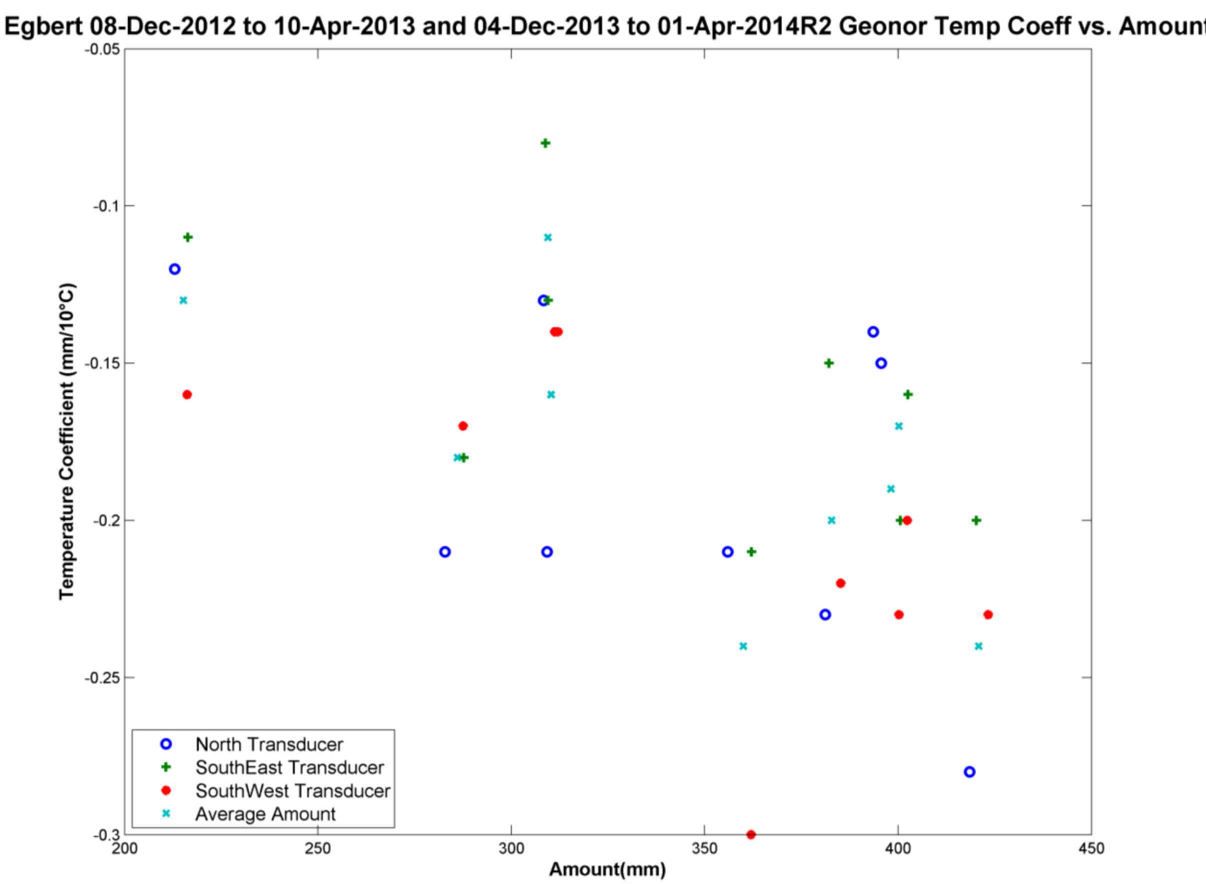


The table below lists the temperature coefficients and the corresponding amounts of the transducers for some of the no-precipitation periods in the 2012-2013 and 2013-14 winters.

	North Transducer		Southeast Transducer		Southeast Transducer		Average	
	Temp Coeff (mm/10C)	Amount (mm)	Temp Coeff (mm/10C)	Amount (mm)	Temp Coeff (mm/10C)	Amount (mm)	Temp Coeff (mm/10C)	Amount (mm)
Dec 13-15, 2012	-0.12	212.94	-0.11	216.35	-0.16	216.16	-0.13	215.15
Jan 15-16, 2013	-0.21	282.86	-0.18	287.75	-0.17	287.49	-0.18	286.03
Feb 25-26, 2013	-0.21	355.93	-0.21	362.12	-0.3	361.96	-0.24	359.97
Mar 28-30, 2013	-0.14	393.58	-0.2	400.56	-0.23	400.23	-0.19	398.12
Apr 4, 2013	-0.15	395.58	-0.16	402.58	-0.2	402.33	-0.17	400.16

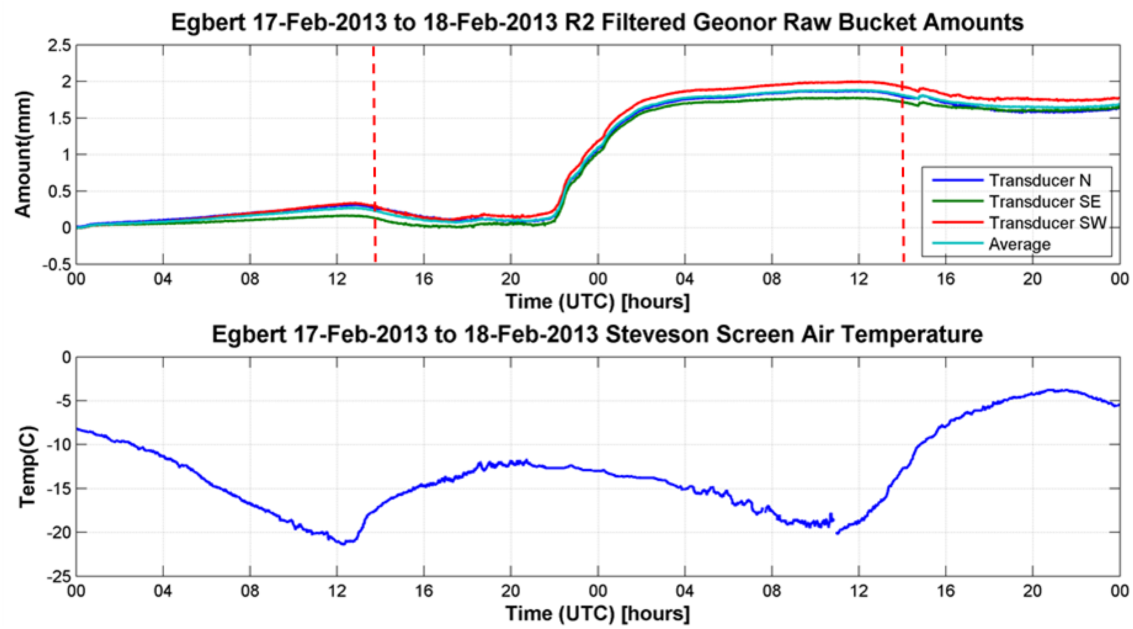
Dec 28-29, 2013	-0.13	308.34	-0.08	308.8	-0.14	311.21	-0.11	309.45
Jan 1-4, 2014	-0.21	309.17	-0.13	309.50	-0.14	312.07	-0.16	310.25
Feb 11-13, 2014	-0.23	381.19	-0.15	382.08	-0.22	385.12	-0.20	382.80
Mar 17-18, 2014	-0.28	418.51	-0.2	420.22	-0.23	423.29	-0.24	420.82

Below is a plot of temperature coefficients versus amounts in the bucket. The general trend shown is similar to that in [4].



8 Appendix C – Adjustment for temperature

The gauge amount and temperature for the event (17/02/2013 13:40, 18/02/2013 14:05) are shown below.



The dotted, vertical red lines indicate the manual observation times.

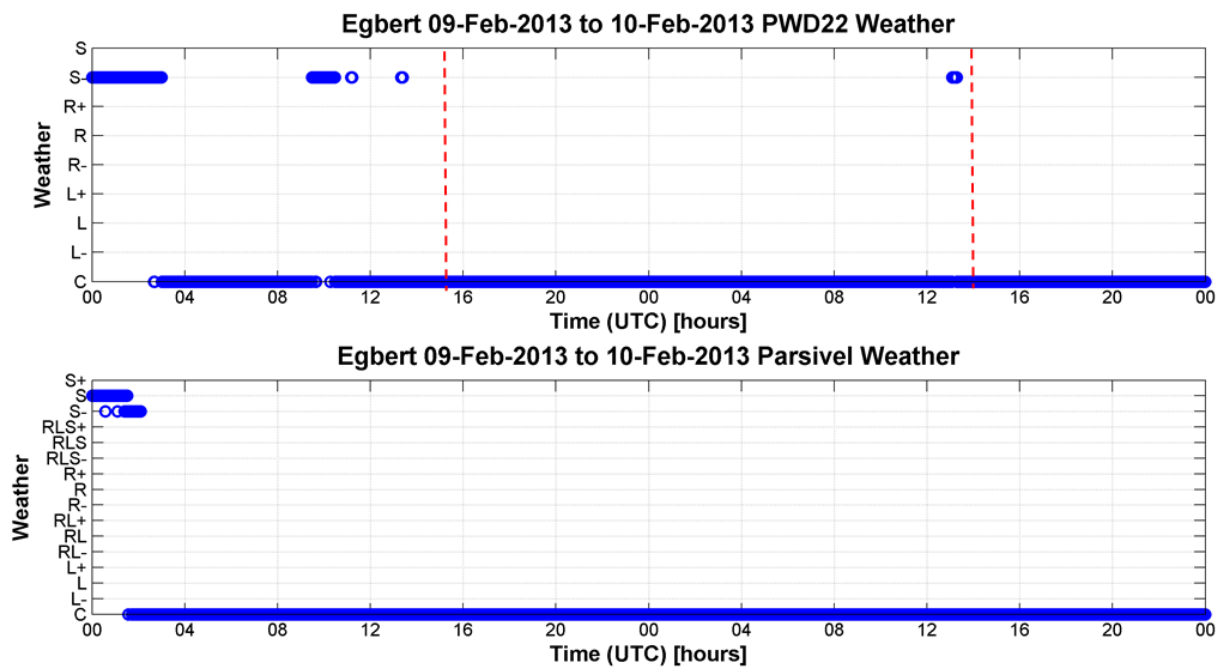
The adjusted amounts for temperature effect are given in the table below.

Start Date Time	End Date Time	R1 Inc (mm)	R2 Inc (mm)	CE	Adj R2 Inc (mm)	Adj CE
26/12/2012 15:35	27/12/2012 14:11	12.86	11.78	0.916	11.77	0.915
27/12/2012 14:11	28/12/2012 13:43	1.19	1.13	0.953	1.11	0.933
29/12/2012 14:19	30/12/2012 14:05	3.76	3.53	0.938	3.46	0.920
25/01/2013 13:42	26/01/2013 13:40	1.54	1.44	0.933	1.45	0.942
07/02/2013 15:13	08/02/2013 15:50	30.13	28.15	0.934	28.10	0.933
08/02/2013 15:50	08/02/2013 22:39	10.47	10.05	0.960	10.05	0.960
08/02/2013 22:39	09/02/2013 15:30	2.13	2.02	0.949	2.00	0.939
17/02/2013 13:40	18/02/2013 14:05	1.93	1.57	0.815	1.66	0.860
20/02/2013 13:17	21/02/2013 13:57	1.34	1.28	0.952	1.17	0.873
03/03/2013 13:09	04/03/2013 15:05	1.6	1.48	0.925	1.54	0.962
14/12/2013 20.56	15/12/2013 18:48	6.58	5.79	0.879	5.92	0.900
15/12/2013 18:48	18/12/2013 17:00	4.29	4.03	0.939	4.12	0.960
21/12/2013 20:25	22/12/2013 19:20	23.86	20.40	0.855	20.38	0.854
19/01/2014 15:18	20/01/2014 15:24	2.86	2.46	0.860	2.35	0.822
20/01/2014 15:24	21/01/2014 13:29	1.92	1.73	0.903	1.54	0.802
24/01/2014 15:31	25/01/2014 16:05	3.58	3.44	0.960	3.59	1.003
26/01/2014 19:45	27/01/2014 16:09	2.31	2.28	0.985	2.28	0.987
04/02/2014 15:31	05/02/2014 15:47	3.6	3.20	0.889	3.25	0.903
05/02/2014 15:47	06/02/2014 15:52	4.09	3.87	0.946	3.83	0.936

09/02/2014 14:50	10/02/2014 15:28	2.04	1.92	0.944	1.99	0.975
17/02/2014 14:55	18/02/2014 15:28	3.15	2.74	0.871	3.00	0.952
28/02/2014 15:46	01/03/2014 15:37	1.35	1.25	0.926	1.42	1.052
04/03/2014 15:45	05/03/2014 16:29	2.18	2.17	0.998	2.24	1.028
05/03/2014 16:29	06/03/2014 15:50	1.1	1.12	1.019	1.07	0.973
12/03.2014 12:16	12/03/2014 21:18	7.58	6.28	0.829	6.14	0.810
R1, R2 Sum (mm)		137.44	125.11		125.43	

9 Appendix D – Frost on R1 Gauge

The weather on February 9 and 10, 2013 are shown below.



The events with adjustment for temperature and frost are shown below.

Start Date Time	End Date Time	R1 Inc (mm)	R2 Inc (mm)	CE	Adj R1 for frost (mm)	Adj R2 for T (mm)	Adj CE for T & frost
25/01/2013 13:42	26/01/2013 13:40	1.54	1.44	0.933	1.47	1.45	0.986
17/02/2013 13:40	18/02/2013 14:05	1.93	1.57	0.815	1.91	1.66	0.869

10 Appendix E – The Effect of Different R1 and R2 limits, Effect of Different Temperature limits and Moving Average Filter Widths

We vary the limit for the R1 and R2 increments and its effects are given below.

R1 R2 Limit (mm)	Number of Events	Mean CE	St. Dev. (CE)	Slope of Linear Regression of CE vs. Wind Speed	R^2
1.5	19	0.914	0.052	-0.00189	0.0021
1	25	0.923	0.05	-0.00572	0.02
0.8	30	0.934	0.061	-0.00522	0.01
0.5	36	0.928	0.084	0.0097	0.018
0.3	47	0.948	0.11	0.0233	0.064
0.1	54	0.96	0.15	0.0346	0.067

The mean CE is around 93% to 96%. The standard deviation of CE increases as the limit for R1 and R2 decreases.

We vary the temperature limit for solid precipitation and its effects are given in the table below.

Temp Limit (°C)	Number of Events	Mean CE	St. Dev. (CE)	Slope of Linear Regression of CE vs. Wind Speed	R^2
-5	19	0.936	0.045	0.00285	0.0066
-2	25	0.923	0.05	-0.00572	0.02
0	33	0.927	0.066	-0.00245	0.0017
2	48	0.906	0.09	-0.0109	0.021
5	61	0.903	0.099	-0.0129	0.022

We vary the moving average filter width and its effects are given in the table below.

MA width (minute)	Number of Events	Mean CE	St. Dev. (CE)	Slope of Linear Regression of CE vs. Wind Speed	R^2
1	25	0.923	0.05	-0.00572	0.02
2	25	0.923	0.051	-0.00571	0.02
5	25	0.923	0.051	-0.00569	0.019
10	25	0.923	0.051	-0.00577	0.02

11 References

[1]. C-SPICE – Precipitation Gauge Heating Summary, May 17, 2013.

[2]. CARE Commissioning Report Revised - Appendix A: Proof of Performance (POP) Forms, 2013 October 29.

[3]. Colli, M., Snow machine tests, #2 report, Wednesday 10th April 2013, SPICE teleconference.

[4]. Duchon, C.E., Field measurements of temperature sensitivity in Geonor vibrating-wire transducers, American Meteorological Society meeting, 2004 https://ams.confex.com/ams/pdfpapers/69938.pdf.

[5]. Earle, M and P. Raczynski, Manual observation procedures at CARE, Observing Systems and Engineering, Meteorological Service of Canada, V4, 2013 Feb 6.

[6]. Geonor T-200B Series Precipitation Gauge Instruction Manual, 600mm, 1000mm, and 1500mm capacity options, Campbell Scientific (Canada) Corp. September 2011, Rev. 10.7.

[7]. Goodison, B.E. and P.Y.T. Louie and D. Yang, WMO Solid Precipitation Measurement Intercomparison, Final Report, WMO/TD-No. 872, 1998. 212 p.

[8]. Mohamed, R and J. Hoover, CARE Geonor T200B Precipitation Gauge Field Verification, July 15-26, 2013.

[9]. Ohaus Explorer Analytical and Precision Balances, Brochure.

[10]. Ohaus Explorer Analytical and Precision Balance (S/N 8033021016), Calibration Data Report by M & L Testing Equipment (1995) Inc. on January 17, 2012 and July 22, 2013.

[11]. Smith, C.D. and D. Yang, An assessment of the Geonor T-200B inside a large octagonal double fence wind shield as an automated reference for the gauge measurement of solid precipitation, 6.1 AMS conference, 2008.

[12]. Smith, Craig D. 2009. The relationships between snowfall catch efficiency and wind speed for the Geonor T-200B precipitation gauge utilizing various wind shield configurations, *proc. 77th Western Snow Conference*, Canmore, 115-120.

[13]. Yang, D., and A. Simonenko. 2013. Comparison of winter precipitation measurements by six Tretyakov gauges at the Valdai experimental site, Atmosphere-Ocean, p. 1-15.