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An assessment of two automated snow water equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment

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Abstract. During the WMO Solid Precipitation Intercomparison Experiment (SPICE), automated measurements of snow water equivalent (SWE) were made at the Sodankylä (Finland) and Caribou Creek (Canada) SPICE sites during the northern hemisphere winters of 2013/2014 and 2014/2015. Supplementary intercomparison measurements were made at Fortress Mountain (Kananaskis, Canada) during the 2013/2014 winter. The objectives of this analysis are to assess automated SWE measurements against a reference, comment on their performance, and make recommendations on how to best use the instrument and interpret its measurements. Sodankylä, Caribou Creek and Fortress Mountain hosted a Campbell Scientific CS725 passive gamma radiation SWE sensor. Sodankylä also hosted a Sommer Messtechnik SSG1000 snow scale. The CS725 measurement principle is based on measuring the attenuation of soil emitted gamma radiation by the snowpack and relating the attenuation to SWE. The SSG1000 measures the mass of the overlying snowpack directly by using a weighing platform and load cell. Manual SWE measurements were obtained at the SPICE sites on a bi-weekly basis over the accumulation/melt periods using bulk density samplers. These manual measurements are considered to be the reference for the intercomparison. Results from Sodankylä and Caribou Creek showed that the CS725 generally overestimates SWE as compared to manual measurements by roughly 30 to 35 % with correlations (r^2) as high as 0.99 for Sodankylä and 0.90 for Caribou Creek. The RMSE varies from 30 to 43 mm water equivalent (w.e.) and 18 to 25 mm w.e. at Sodankylä and Caribou Creek respectively. The correlation at Fortress Mountain was 0.94 (RMSE of 48 mm w.e.) with no systematic overestimation. The SSG1000 snow scale, having a different measurement principle, agreed quite closely with the manual measurements at Sodankylä throughout the intercomparison periods (r^2 as high as 0.99 and RMSE from 8 to 24 mm w.e.). When the SSG1000 is compared to the CS725, the agreement is linear until the start of seasonal melt when the positive bias in the CS725 increases substantially relative to the SSG1000. Since both Caribou Creek and Sodankylä have sandy soil, water from the snowpack readily infiltrates into the soil during melt but the CS725 does not differentiate this water from the un-melted snow. This issue can be identified, at least during the spring melt, with soil moisture and temperature observations like those measured at Caribou Creek. With a less permeable soil and surface runoff, the increase in the instrument bias during melt is not as significant, as shown by the Fortress Mountain intercomparison.

1 Introduction

The measurement of snow water equivalent (SWE) is vital for flood and water resource forecasting, drought monitoring, climate trend analysis, and hydrological and climate model initialization (Barnett et al., 2005; Gray et al., 2001; Bartlett et al., 2006; Laukkanen, 2004). Many of these applications require accurate and timely information about how much water is being held within the snowpack (Pomeroy and Gray, 1995). SWE measurements can be made in-situ, either manually or via automated instrumentation, or derived from remote sensing platforms and are usually expressed as units of mass per area (kg m^{-2}) or millimetres of water equivalent (mm w.e.).

Manual measurements of SWE are typically made using a multi-point bulk density sampling technique along an established transect or snow course (WMO, 2008). Snow course measurements are often time consuming and expensive, especially if required in remote locations (Pomeroy and Gray, 1995). This means that manual SWE measurements may be infrequent or only undertaken when the snowpack is estimated to be at its seasonal maximum. Prohibitive costs of manual snow course observations have led to the reduction of these measurements by many agencies, including Environment Canada, where operational snow course numbers have decreased from over 100 in the 1980s to less than 30 (Barry, 1995; Brown et al, 2000). Since the early 1990s, manual SWE measurements have been augmented or replaced by remote sensing techniques such as passive microwave retrievals (Goodison and Walker, 1995) but these techniques still require accurate and reliable in-situ measurements for ground-truthing and retrieval development (Derksen et al., 2005; Takala et al., 2011).

With the reduced availability of manual SWE measurements, automated instruments for the measurement of SWE are becoming more necessary and more commonplace. Snow pillows have been used for the automated measurement of SWE in remote locations since the 1960s (Beaumont, 1965) by measuring the overlying pressure of the snowpack on a fluid filled bladder. The SNOTEL network in the United States is based on snow pillow measurements (Serreze et al., 1999). More recently, similar measurements are obtained using snow scales that use a weighing surface and load cell to measure the weight of the overlying snow (Beaumont, 1966; Johnson et al.,2007). Several indirect methods exist to measure SWE that include the use of neutron probes (Harding, 1989) in which a radiation source is placed under the snowpack and the scattering of neutrons through the snow is measured by a detector. Cosmic ray proton probes (Kodama et al., 1979; Rasmussen et al., 2012) work in a similar manner but do not require an active source. The probes described by Kodama and Nakai are installed under the snow while the system described by Rasmussen et al. (called COSMOS) is installed above the snow. Kinar and Pomeroy (2007; 2015a) outline a method of non-invasive sonic reflectometry through the snowpack to determine snow density, liquid water content, and temperature. Other passive radiation sensors are mounted above the surface and measure the attenuation of naturally emitted radiation from the soil as it passes through the snowpack and then relates this attenuation to SWE content (Choquette et al., 2008; Martin et al., 2008). Each of these instruments and techniques have advantages and disadvantages, which are not discussed here (see Kinar and Pomeroy (2015b) for a more comprehensive description of snow measurement methods and related issues). Rather, this analysis assesses the use and accuracy of two instruments that were tested during the WMO-Solid Precipitation Intercomparison Experiment

(SPICE; Nitu et al., 2012; Rasmussen et al., 2012), the Campbell Scientific CS725 and the Sommer Messtechnik SSG1000 snow scale.

One of the objectives of the WMO-SPICE project is to assess the performance of automated instrumentation for the measurement of snow, including snow on the ground (SoG). This is accomplished by comparing the tested instruments to an established reference measurement. In total, fifteen countries are participating in the WMO-SPICE project with about 20 intercomparison sites. Of these, 7 countries and 9 intercomparison sites are hosting SoG instrumentation. The instrumentation for SPICE has either been provided by the instrument manufacturers or by the site hosts. For SoG, 13 different instruments are under test with 9 measuring snow depth and 4 measuring SWE. The CS725 and the SSG1000 SWE instruments examined here were installed at the Sodankylä (Finland) and Caribou Creek (Canada) intercomparison sites (Fig. 1). To supplement the CS725 data collected for WMO-SPICE, data was added from an additional CS725 instrument installed at the Fortress Mountain ski area in the Kananaskis region of the Canadian Rocky Mountains.

2 Instrumentation and Methods

2.1 Campbell Scientific CS725

The CS725 (Fig. 2 left) is a passive gamma sensor developed by Hydro Québec in collaboration with Campbell Scientific (Canada) Corp. (Choquette et al., 2008; Martin et al., 2008). The instrument is installed above the snow surface and determines SWE by measuring naturally emitted gamma radiation from Potassium and Thallium sources in the soil that are attenuated by the snowpack. Each gamma ray detected by the sensor element is counted over a user defined period, the resulting distribution is compared to the distribution when there was no snow cover, and the difference is used to calculate SWE. The sensor field of view (FOV) is approximately 60° from centre resulting in a field of view (FOV) of approximately 80m^2 when installed 3 m above the snowpack and with the collimator attached. The collimator serves to shield the instrument from gamma rays emitted from sources that are not in the target area. The effective range of the instrument is 0 to 600mm w.e. with a measurement accuracy of +/- 15mm w.e. from 0 to 300 mm w.e. and 15% from 300 to 600mm w.e. (Campbell Scientific CS725 Manual, https://s.campbellsci.com/documents/ca/manuals/cs725_man.pdf)

The CS725 (originally known as the GMON3) has been previously field tested by Hydro Québec (as referenced above) as well as by Wright et al (2011). Previous results by Choquette et al (2008) show an average error of +18 % when comparing to 8 manual snow cores over 3 seasons in Quebec but get a somewhat better agreement with snow pit densities (with an average error of +5 %) but only had 4 samples over 2 seasons. Wright et al. (2011) showed intercomparison results between GMON3 sensors and snow pillows, precipitation gauges, and snow courses at Sunshine Village (Alberta, Canada) and Tony Grove Ranger Station (Utah, USA). Results showed high correlations between the sensor and (unadjusted) accumulated precipitation (0.99) and between the sensor and snow pillow observations (0.99) but lower correlations (0.83) with snow course observations (during one season at Sunshine Village). The authors question the quality and inherent biases in the snow course samples but do not comment on the sources of error or the proximity of the snow course to the instrument.

One large potential source of error for the CS725 is from a poor pre-snowpack calibration or change to this calibration from overwinter soil moisture changes (Gray et al., 1985), infiltration of snowmelt water into soils (Gray et al., 2001) or formation of a basal ice layer between the snowpack and the soil (Lilbaek and Pomeroy, 2008). The calculation of SWE is based on gamma ray counts during wet and dry periods with no snow cover. When these estimated offsets are incorrect, either due to incorrect measurements or faulty assumptions, or if moisture levels in the soil change significantly prior to freeze-up or during winter or spring melting, then the SWE estimates derived from the sensor are less reliable. The approximate error associated with an inaccurate gravimetric soil moisture calibration, as provided by the manufacturer, is roughly 1 mm w.e. of SWE for 1 % soil moisture error.

The two CS725 instruments for WMO-SPICE were both installed in October 2013 and operated over the Northern Hemisphere winters of 2013/2014 and 2014/2015. Both instruments were mounted so that the bottom of the instrument was approximately 2 m above the ground. Both instruments were installed with the manufacturer provided collimator. Data was output every 6 hours. Each instrument performed in a reliable manner exhibiting a measurement rate higher than 95 % at both sites over the course of the two winter seasons. No malfunctions were noted and no maintenance was required. The instrument at Sodankylä was moved approximately 10m during the summer of 2014 to avoid some buried cables but any potential impact of the move are considered to be negligible.

The third CS725 used in this analysis was not a WMO-SPICE instrument but was loaned to the University of Saskatchewan for testing and intercomparison by the instrument manufacturer. This instrument was installed in a clearing near the Fortress Mountain ski resort in the Kananaskis Valley, Alberta. The CS725 was mounted at a height of approximately 3.5 m above the ground. The distance to the trees around the instrument was approximately 10m from the centre of the instrument FOV, putting them outside of the response area. Data collected by this instrument from October 2013 through June 2014 is used in this analysis. Like the other CS725 instruments, SWE data was output every 6 hours.

2.2 Sommer SSG1000

The SSG1000 snow scale (Fig. 2 right) manufactured by Sommer Messtechnik measures SWE through the use of a weighing platform and load cells. Unlike the CS725, it makes a direct measurement of the weight of the snowpack on top of the weighing platform and converts this weight to SWE. The entire platform consists of 7 perforated panels, each 0.8 m x 1.2 m, that are attached to a frame and installed level with the surface of the ground. The entire instrument surface is 2.8 m x 2.4 m (6.72 m^2) but only the centre panel is weighed by the load cell. According to the manufacturer, the purpose of the larger surface surrounding the centre measurement panel is to stabilize the overlying snowpack and prevent ice bridging (http://www.sommer.at/en/products/snow-ice/snow-scales-ssg). The SSG1000, as tested for WMO-SPICE, has a measurement range of 0 to 1000 mm w.e. SWE, and a manufacturer stated resolution and accuracy of 0.1 mm w.e. and 0.3 % of full scale, respectively.

Instrument intercomparisons that included the SSG1000 have been limited but some results are reported by Stranden and Grønsten (2014) who showed parallel SWE measurements between snow pillows, snow scales, and manual snow courses. With mitigating circumstances (e.g. drifting and scale issues), they concluded that the measurement

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surface area had an impact on the measurement quality and that the Sommer scale gave "promising results" but that further intercomparison was required.

The SSG1000 in this analysis, and the only snow scale provided by the manufacturer for WMO-SPICE, was installed in the Sodankylä Intercomparison Field. Data collection from the instrument started in October 2013 and continued for the 2013/2014 and 2014/2015 Northern Hemisphere winters. The SSG1000 was located in the North East quadrant of the Sodankylä SPICE Intercomparison Field, approximately 22 m southeast of the original location of the CS725. SWE observations from the instrument were recorded once per minute during the two intercomparison seasons. The instrument worked in a reliable manner during the accumulation periods but malfunctioned due to water damage to the electronics late in the spring of 2014 and again early spring of 2015, resulting in 83 % and 67 % of the 1-minute measurements being useable for the respective intercomparison periods. Other than this, no malfunctions were reported or maintenance required during the intercomparison. A SSG1000 was also installed at the Fortress Mountain Ski Resort site near the CS725 by the University of Saskatchewan but failed to operate during the comparison winter due to damaged electronics from a possible lightning strike. The sensitivity of this instrument to atmospheric electrical phenomenon, even when located in a sheltered forest clearing is a concern.

2.3 Reference SWE measurements

The reference SWE measurements for this intercomparison are bulk density snow samples made with a snow sampling tube of a known diameter that has one end capable of penetrating and cutting into the snowpack. The tube is inserted into the snowpack down to the surface of the ground and the sample is extracted. Along with the sample, the depth of the snowpack is also obtained. The sampled snow is then either bagged and weighed or is weighed inside the tube using a cradle and balance. The snow sampler used in Canada is different than the tube used in Finland and these differences, as well as any other differences in sampling technique, are described below.

At Caribou Creek, the reference SWE measurements were obtained using an ESC-30 snow tube with a 30 cm^2 cutting area. Farnes et al. (1983) demonstrated that the ESC-30, when used correctly, has a mean measurement error less than 0.5 %. Bulk density samples at Caribou Creek were taken just inside the footprint of the CS725, bagged, and weighed. These manual SWE measurements were made about every two weeks in conjunction with a full 5 point snow course across the Intercomparison Field and into the forest canopy on each side.

At Sodankylä, the reference SWE measurement was made using a Finnish bulk density sampling tube, with a sampling area of 78.54 cm^2, and balance (Kuusisto, 1984) at roughly the same location in the Intercomparison Field every two weeks. During the winter of 2013/2014, the bulk density SWE sample was obtained approximately 12 m from the centre of the CS725 FOV and approximately 16m from the centre of the SSG1000. In 2014/2015, after the CS725 was moved, the manual sampling was done approximately 6m from the CS725 FOV and approximately 25 m from the SSG1000.

An ESC-30 snow tube was used at the Fortress Mountain site. A full snow survey was conducted at the site once per month, transitioning to bi-weekly during the melt period. The actual snow survey was conducted through the forested area and not the clearing where the instrumentation is located, but three concurrent samples of SWE were obtained in the clearing closer to the CS725.

2.4 Intercomparisons

The intercomparisons are not consistent amongst the three sites because of the different instrumentation and manual methods for measuring reference SWE. At Sodankylä, the CS725 and the SSG1000 can both be compared with the manual SWE measurements made nearby, although the manual measurement is not within the FOV of either instrument. The timestamps of both instruments were matched as closely as possible to the manual observation time. Since the CS725 only reports every 6 hours, the output measurement closest to the manual observation time was used for the intercomparison. Since the SSG1000 reports every minute, no time adjustment was necessary. The same procedure was used to compare the CS725 to the SSG1000. No SSG1000 was present at Caribou Creek or operating at Fortress Mountain so the comparisons at these sites were only between the CS725 and the manual SWE measurements. For the CS725, which outputs a SWE value derived from both the Potassium (K) and Thallium (Tl) counts, the manufacturer suggests that the output with the higher counts is generally the most reliable. For Sodankylä, the K/Tl ratio is always greater than 1 (varying from 3.5 to 8.0) indicating that the Potassium counts are greater than the Thallium counts. For Caribou Creek, the ratio varies from 2.8 to 4.0. For Fortress Mountain, the ratio varies from 0.3 to 8.5 but is above 1 approximately 70 % of the time. Therefore, the CS725 analysis is based on the Potassium output although the statistics for Thallium are shown in brackets in Tables 1 and 4. This will allow us to determine if there are any obvious differences in the statistics related to the output derived from one source or the other.

3 Results and Discussion

3.1 Sodankylä

3.1.1 CS725 vs Manual

The comparison between the CS725 measurements and the manual SWE observations are shown in Fig. 3 with the Potassium output in red circles and the Thallium output in blue triangles. The black line in the figure represents the 1:1 line. Throughout the intercomparison periods at Sodankylä, the CS725 overestimates SWE on average by 30 % as compared to the manual measurements. The regression analysis coefficients and summary statistics are listed in Table 1. The statistics are provided for each individual season and for the two seasons combined. The statistics for the individual seasons are also refined further to show results for the periods prior to snow melt (determined as the point of maximum seasonal SWE). This will help to eliminate the effects of snow melt on both the manual measurement and the various potential impacts on the CS725 measurement.

From Table 1, the regression analysis for the CS725 as compared to manual SWE over the entire season results in a slope (β) of 1.24 for 2013/2014 and 1.06 for 2014/2015. The difference in β between the K and Tl outputs is small. The offsets (ε) for the entire seasons are 8.77 mm w.e. for 2013/2014 increasing to 26.9 mm w.e. for 2014/2015. The correlation coefficient, r^2, is 0.92 for 2013/2014 and 0.96 for 2014/2015. With the period of seasonal melting eliminated from the analysis, the impact on β and ε are relatively small although the offset ε decreases almost 9 mm w.e. and 4 mm w.e. for the respective seasons. The pre-melt r^2 increases to 0.97 and 0.99 for the 2013/2014 and 2014/2015 seasons respectively suggesting that more scatter is introduced into the relationship during the melting period. This is expected, as the snow does not melt evenly at the site and a melting snowpack is more difficult to sample with a snow tube. Some of the difference in the relationships from one season to the next is possibly due to the relocation of the sensor but this is difficult to ascertain.

Figure 4 shows the time series for the 2013/2014 (left) and 2014/2015 (right) seasons at Sodankylä. Superimposed on this graph are the measurements made by the SSG1000 that will be discussed further in the next section. In this figure, the overestimation of the CS725 (red and blue lines) can be seen when compared to manual SWE (black circles). In general, the instrument trends are the same as for the manual measurements with differences between the measurements increasing after the start of the melt periods. Figure 5 shows the difference between the CS725 (red, difference divided by 2 for visualization) and the measured air temperature (blue) through the two seasons. Although it appears that the difference between the measurements are simply increasing with time (or SWE amount), we believe that this increase is a result of melting in the snowpack which occurs during some relatively warm days. In 2013/2014 (Fig. 5, left), a large increase in the difference occurs after the > 0 °C temperatures in mid to late April. In 2014/2015 (Fig. 5, right), there is a moderate increase after some > 0 °C temperatures in March but a much larger jump after the beginning of the melt period in April.

3.1.2 SSG1000 vs Manual

The time series of the SSG1000 measured SWE, also shown in Fig. 4, suggests a close relationship with the manually measured SWE. The comparison statistics in Table 2 for the regression analysis shown in Fig. 6 indicate that the r^2 for the entire 2014/2015 period is quite good at 0.99 but is only 0.84 for 2013/2014. However, the SWE data from the SSG1000 is not available for the seasonal snow melt period in 2014/2015. To have a consistent intercomparison for the two seasons, the melt period (post maximum SWE) was removed from the 2013/2014 period and the r^2 becomes 0.97, very similar to 2014/2015. Combining the two seasons, the slope of the regression, β, becomes 0.99 with an offset ε of -7.27 mm w.e. with an r^2 of 0.88. The average bias for the two seasons combined is -11 %.

The outliers in Fig. 6 can be attributed to the melt period in late April to May 2014 but it is difficult to ascertain if the errors are related to the instrument or to the manual measurement. The most likely explanation is the differential melt of the snowpack at the site combined with errors associated with manually sampling a melting snowpack.

3.1.3 CS725 vs SSG1000

The intercomparison with manual measurements for both the CS725 and the SSG1000 are suggesting that the agreements are the most favourable prior to snow melt. Figure 7 shows the relationship between the CS725 and the SSG1000 for both seasons at Sodankylä with the 2014/2015 season shown in red circles and the 2013/2014 season shown in blue circles (changing to blue triangles at the approximate onset of seasonal melt). The relationship for both years appears to be linear up to the time where maximum SWE is reached. At the onset of melt, the relationship between the instruments (2013/2014 only due to data unavailability for 2014/2015), shown by the magenta circles, deviates substantially from linear. This is confirmed by Table 3 which shows a higher r^2 when the 2013/2014 melt period is not included in the analysis.

Some of the difference between the two instruments during melt can certainly be attributed to differential melt in the intercomparison field. We know that both sensors agree less well with manual SWE measurements after the onset of melt. Using hourly web camera photos from Sodankylä (not shown), we can qualitatively confirm that some areas of the intercomparison field melt faster than others due to exposure. However, it is still difficult to ascertain how much of the difference between the instrument measurements during melt is due to the unequal melting rates and how much can be attributed to the difference in measurement principle of the instruments. While meltwater drains away from the SSG1000 and is no longer measurable as SWE, meltwater that infiltrates into the top layer of the soil could still be interpreted as SWE by the CS725. This issue is discussed further in subsequent sections.

3.2 Caribou Creek

3.2.1 CS725 vs Manual

The comparison of the CS725 instrument and the manual SWE measurements made at Caribou Creek are shown in Fig. 8 and summarized in Table 4. As with Sodankylä, the difference between the two sensor outputs (Potassium vs. Thallium) is negligible. Also like Sodankylä, the CS725 at Caribou Creek consistently overestimates total SWE on average by 35 %. However, the relationships between the instrument and the manual SWE measurements are different than at Sodankylä. At Caribou Creek, the slopes of the regression line, β, are less than 1 for all scenarios in Table 4 with the exception of the pre-melt SWE period in 2014/2015. The offsets, ε, are all larger than seen at Sodankylä, with the pre-melt SWE period in 2014/2015 being the exception once again. The r^2 values range from 0.90 for the combined (2013/2014 and 2014/2015) data to 0.55 for the pre-melt SWE period in 2014/2015. Correlations are lower at Caribou Creek for several reasons. The spatial and seasonal variability are greater at this site and the sample size is lower. This is especially the case for 2014/2015 where sample size is lower due to a shorter and more variable winter where melt and re-freeze occurred several times over the course of the season. Melting and re-freezing not only results in higher spatial variability, but also makes the manual SWE measurement more difficult and prone to error. Eliminating the pre-melt SWE period improved the comparison statistics for 2013/2014 but made the statistics for 2014/2015 much worse due to the reduced sample size.

For both the 2013/2014 and 2014/2015 seasons, the time series for Caribou Creek (Fig. 9) shows a rapid increase in SWE in early winter related to heavier, wet snowfall events that most likely began as rain and transitioned to snow. For 2013/2014, the CS725 time series generally follows the trend of the manual SWE measurements with a large deviation developing mid- to late-March with the onset of seasonal melting. Figure 10 shows the time series of the difference between the CS725 and manual SWE (in red, divided by 2 for visualization purposes) and the temperature time series (blue) for both seasons. In 2013/2014 (Fig. 10 left), there is an increase in the difference that occurs in late January. This could be due to a melt period where temperatures at the site exceeded 4 °C preceding the increase in the instrument bias. A much larger jump in the difference occurs mid-March possibly due to significantly higher temperatures (exceeding 10 °C) earlier that month. In 2014/2015 (Fig. 10 right), the deviation between the measurements occurs earlier in the season (mid- to late-January) coinciding with a January snow melt period characterized by above 0 °C air temperatures and high wind speeds (not shown). Differences decrease after snowfall events in February only to increase again after the start of seasonal melting in March.

3.2.2 Soil Moisture and Temperature

After the 2013/2014 winter, a profile of Stevens Hydra Probe soil moisture sensors was installed within the FOV of the CS725 at Caribou Creek. The objective was to monitor changes in soil moisture that might influence the sensor's soil moisture calibration at the autumn/winter transition or changes in soil moisture throughout the winter that might be related to mid-winter snowpack melt, both of which could cause the instrument to overestimate as compared to the manual measurement. The instruments were installed at three depths: 0 to 5 cm (vertically), 5 cm (horizontally) and 20 cm (horizontally). Unfortunately, the probes only measure liquid water so the analysis is limited to when the soil temperatures (also measured by the probe) are above 0 °C.

Figure 11 shows the time series of soil moisture near the surface (0 to 5cm) for the 2014/2015 season. The red markers indicate when the soil temperature at this level is above 0 °C. It is easy to see from the time series when the liquid soil moisture (near the surface) freezes in late fall resulting in a rapid drop in measured liquid water content. Following the freezing of the near surface layer, which occurs 8 November 2014, the measured soil moisture in this layer remains fairly static until mid-March 2015 when a period of positive air temperatures (Fig. 10 right) raises the near surface soil temperatures above freezing, transitioning frozen soil moisture to liquid and allowing for infiltration of snow melt water into the sandy soil at this site.

The freezing of the 0 to 5 cm depths in early November is preceded by rain/snow events in late October that are represented by the large jump in CS725 SWE shown in Fig. 9 (right) and confirmed with snow depth measurements (not shown). During the transition from rain to snow and prior to the surface freezing, Fig. 11 shows fluctuations in near surface soil moisture related to the precipitation events in late October and early November. Considering that the soil moisture calibration of the sensor was entered as 0.10 (gravimetric water fraction), the increase in measured volumetric water content to 0.18 prior to freezing has the potential to create a perpetuating offset in the CS725 SWE estimates and may explain at least some of the bias shown by the instrument. Initial estimates provided by Campbell Scientific (personal communication, 2015) suggest that a 10 % increase in gravimetric soil moisture would approximate a 10 mm w.e. response in the SWE estimate of the CS725. Using these approximation would explain roughly 30 % of the CS725 offset over the 2014/2015 period. More work is needed to establish some confidence in these early season SWE measurements that are made before the ground freezes and the soil moisture content becomes less mobile.

In addition to the offset in the CS725 SWE measurements that occurs at the beginning of the season, it was anticipated that the rapid increase in the difference between the CS725 and Manual SWE at the end of January 2015 could also be attributed to a change in near surface soil moisture, as this was a time of mid-season snow melt. However, a change in the liquid soil moisture during the melt period could not be detected so it is unlikely that the increase in the instrument offset can be attributed to infiltration of melt water into the sandy soil. A more plausible explanation are manual measurement errors that could result from attempting to sample a complex snow pack containing ice layers in the pack or at the snow/soil interface. Ice layers would have formed due to mid-season melt and re-freezing. The increase in the difference between the manual measurement and CS725 in mid- to late-March could be a result of snow melt infiltrating into the top layers of the sandy soil as the soil thaws or forming a basal ice layer on top of the soil. A corresponding spike in measured soil moisture during early spring snow melt is shown in Fig. 11.

3.3 Fortress Mountain

3.3.1 CS725 vs Manual

The intercomparison of the CS725 instrument and the manual SWE measurements made at Fortress Mountain are shown in Fig. 12 and summarized in Table 5. Unlike the other two sites, the CS725 and manual SWE measurements generally fall on the 1:1 line with no systematic overestimation. This can also be seen in the time series shown in Fig. 13. The slope of the regression line is 0.881 with a small decrease to 0.764 when excluding the melt period. The offset is 32.4 mm w.e. increasing to 84.4 mm w.e. when excluding the melt period. The r^2 is comparable to Sodankylä at 0.92 (increasing to 0.94 by excluding the melt period). It is unfortunate that the sample size is relatively small (n=8) but regardless, the instrument compares quite well to the manual measurements at this site. Unlike Caribou Creek and Sodankylä that both have very sandy soils, there doesn't appear to be an increase in the instrument bias as compared to the manual measurements following a mid-winter or end of season melt event. In fact, from Fig. 14, we see the bias drop into high negative numbers after a melt period at the end of March 2014 and again at the end of April 2015. The absence of a trend of increasing bias following melt is most likely due to low infiltration of meltwater into these saturated frozen soils. The water here may be more inclined to drain away from the mildly sloping target area rather than infiltrating.

4 Summary and Conclusions

Two automated SWE instruments were tested at two WMO-SPICE sites (Sodankylä and Caribou Creek) and at one additional Canadian site (Fortress Mountain) during the WMO-SPICE intercomparison (Northern Hemisphere) winters of 2013/2014 and 2014/2015. Instrument measurements were compared to periodic manual measurements of SWE at the sites and cross referenced with ancillary measurements of air temperature and soil moisture and soil temperature (at Caribou Creek) to try to determine causality for some of the bias seen in the intercomparison. The objective is not necessarily to determine which instrument makes the most accurate measurement, but to inform users of the best way to use these instruments and of any potential measurement issues that may influence their data interpretation.

Intercomparison results for the CS725 show that it overestimates SWE on average by 30 % and 35 % at Sodankylä and Caribou Creek respectively with higher correlations at Sodankylä (r^2 ranging from 0.92 to 0.99) than Caribou Creek (r^2 ranging from 0.55 to 0.90). The difference in correlations can be attributed to smaller sample size, higher spatial variability of SWE, and ice layers in the snowpack at Caribou Creek. Offsets were generally higher at Caribou Creek which could be indicative of a inaccurate soil moisture calibration of the instrument, a change in soil moisture relative to the calibration prior to or after the soil freezing, or systematic sampling errors in the manual SWE measurement due to a more complex snowpack. Correlations at Fortress Mountain are also quite high (r^2=0.94) with a mean negative bias of less than 5 % which is more comparable to the results of Wright et al. (2011) in similar conditions. At Sodankylä, the bias tends to increase with increasing SWE. This does not occur at either Caribou Creek or Fortress Mountain and the reason for this is not entirely clear. The agreement between the CS725 and the manual SWE measurements are generally better at the two sandy SPICE sites prior to the start of seasonal melt. Seasonal melt has no significant impact on the agreement at Fortress Mountain due to saturated frozen soils that restrict infiltration and a mild slope that promoted runoff of meltwater from the site.

The SSG1000, although only installed at Sodankylä, compared quite well to the manual SWE measurements showing a mean negative bias less than 11 %. It did, however, experience some technical issues early in the 2014/2015 snowmelt period which limited the intercomparison for that season. The correlations were quite high with the r^2 ranging from 0.84 to 0.99. The outliers in the intercomparison occurred in 2013/2014 and were largely related to the melt period late in the season (which was not measured by the instrument in 2014/2015). Removing the melt period in 2013/2014 resulted in a substantial increase in r^2 from 0.84 to 0.97. Although ice bridging of the scale cannot be ruled out, it is difficult to attribute these outliers to the instrument. These outlier are more likely due to increased spatial variability in site SWE during melt or as a result of errors associated with manually sampling the melting snowpack.

The SSG1000 agreed very well with the CS725, especially during the pre-melt period. Although the overestimation of SWE by the CS725 is quite apparent when compared against the SSG1000, the pre-melt r^2 was 0.98 and 0.99 for the two respective seasons. The scatter plot (Fig. 7) clearly shows a very linear relationship between the two instruments (and the increasing bias in the CS725 with increasing SWE) but also very clearly shows the behavior of the CS725 at the onset of melt in March/April of the 2013/2014 season. Independent of the manual measurements, this indicates that the deviation of the CS725 from manual SWE during late season melt is most likely instrument related and a result of infiltration of melt water into the sandy soils at this site. While this meltwater drains away from the SSG1000 platform, the water is still available in the soil to attenuate the gamma radiation signal and therefor the CS725 still interprets this water as snow.

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To examine some potential causality for the bias between the CS725 and manual SWE measurements, the bias was cross referenced with air temperature to qualitatively examine the impact of mid- and late-season snowmelt. At both Sodankylä and Caribou Creek, the bias seems to increase substantially after the occurrence of above freezing air temperatures over the course of the winter, although not all increases in the bias can be attributed to this. As suggested above, the bias seems to increase substantially again at the onset of seasonal melt in March and April. The mechanism for this could be two-fold. The first could simply be the creation of ice layers in the snowpack as a result of freeze/thaw cycles. This would not have an impact on the CS725 measurements but increases the likelihood of errors in the manual SWE measurements. The second could be formation of basal ice layers or infiltration of meltwater into the frozen sandy soil. Installed soil moisture/temperature instruments at Caribou Creek do not show any change related to meltwater infiltration during mid-winter melt, perhaps because either the sandy soil is frozen (in which case the sensors may not register a change) or the meltwater is pooling right at the surface creating a basal ice layer. This basal ice layer would be difficult to accurately sample with a snow tube and therefore result in an underestimation in the manual SWE observation.

The soil moisture/temperature data was used to qualitatively assess the impact of soil moisture change on CS725 measurements at the beginning of a winter season when precipitation generally transitions from rain to rain/snow to snow. In theory, a change in soil moisture leading up to the soil freezing (freezing locks the moisture in place for the season) could impact the sensor's ability to assess that first snowfall event, and potentially perpetuate an offset through the season. Even though the CS725 at Caribou Creek seems to correctly time the SWE accumulations and melt during the fall transition in 2014, measured soil moisture did fluctuate during these events as the soil was not frozen. However, it is difficult to ascertain if this caused the SWE overestimation for these events or more significantly, if the change in soil moisture at transition resulted in the offset for the remainder of the season. It is unfortunate that soil moisture data is not available following the calibration and transition in 2013. During seasonal melting in March 2015 at Caribou Creek, we do see the large increase in soil moisture related to the thawing of the surface and infiltration of meltwater. This infiltration is most likely contributing to the increase in bias of the CS725 sensor relative to the manual SWE measurements made in mid- and late-March 2015.

When comparing SWE instruments to a manual reference, there are several considerations that must be made that ultimately impact the interpretation of the results. We know that the manual measurements of SWE are not free of error. Experience proves that making a snow tube bulk density sample in a snowpack containing ice layers or during melt is difficult and inherently prone to errors. We also have to consider the spatial variability of the snow that we are sampling as the CS725 (and the SSG1000 to a lesser degree) have a much larger measurement footprint that the manual point sample. Taking this and the technical capabilities of the instruments into consideration, both have a good agreement with the manual reference measurements. We have, however, identified the potential for the CS725 measurements to be misinterpreted, especially when deployed over sandy soils and during melting conditions when basal ice layer formation or infiltration to soils can occur. Because of the CS725 measurement principle, it does not differentiate between changes in soil moisture (before freeze up in the fall and after thaw in the spring) or basal ice layers from changes in the SWE of the snowpack. Under these conditions, the CS725 will overestimate the actual SWE. From a hydrological perspective, perhaps it is more useful to include this sub-surface moisture in the estimate as it ultimately impacts the amount of water available for runoff. Nevertheless, it is certainly helpful to co-locate this instrument with ancillary measurements of soil moisture and temperature and snow depth to guide the user in interpreting the data set.

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Tables

Table 1: Regression coefficients and other statistical measures for the multi-season intercomparison of the CS725 with manual SWE at Sodankylä (where β and ε are the slope and intercept of the regression line). Pre-Melt indicates that data occurring after maximum seasonal SWE is omitted from the analysis.

Season	β K(TI)	ε K(TI) mm w.e.	r^2 K(TI)	RMSE K(TI) mm w.e.	Mean Relative Bias (K)	n
2013/2014	1.24(1.27)	8.77(3.17)	0.92(0.92)	43.0(42.2)	30.1%	17
2013/2014 (pre-melt)	1.24(1.28)	0.0123(-6.63)	0.97(0.97)	35.6(33.9)	24.6%	13
2014/2015	1.06(1.13)	26.9(24.2)	0.96(0.96)	36.6(42.2)	30.9%	13
2014/2015 (pre-melt)	1.05(1.12)	23.3(20.2)	0.99(0.99)	30.0(35.7)	28.1%	10
Combined	1.16(1.21)	16.8(11.9)	0.92(0.92)	40.3(42.2)	30.4%	30

Table 2: Regression coefficients and other statistical measures for the multi-season intercomparison of the SSG1000 with manual SWE at Sodankylä (where β and ε are the slope and intercept of the regression line).

Season	β	ε mm w.e.	r^2	RMSE mm w.e.	Mean Relative Bias (K)	n
2013/2014	1.05	-15.5	0.84	24.2	-15.1%	17
2014/2015	0.92	5.45	0.99	7.88	-2.3%	10
Combined	0.99	-7.27	0.88	19.8	-10.8%	27

Table 3: Regression coefficients and coefficient of determination for the multi-season intercomparison of the CS725 with the SSG1000 SWE measurements at Sodankylä (where β and ε are the slope and intercept of the regression line). Pre-Melt indicates that data occurring after maximum seasonal SWE is omitted from the analysis.

Season	β	ε mm w.e.	r^2
2013/2014	1.20	15.7	0.90
2013/2014 (pre-melt)	1.24	4.29	0.98
2014/2015	1.19	11.9	0.99

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Table 4: Regression coefficients and other statistical measures for the multi-season intercomparison of the CS725 with manual SWE at Caribou Creek (where β and ε are the slope and intercept of the regression line). Pre-Melt indicates that data occurring after maximum seasonal SWE is omitted from the analysis.

Season	β K(Tl)	ε K(Tl) mm w.e.	r^2 K(Tl)	RMSE K(Tl) mm w.e.	Mean Relative Bias (K)	n
2013/2014	0.783(0.764)	40.6(46.9)	0.78(0.72)	22.8(27.5)	22.2%	12
2013/2014 (pre-melt)	0.982(0.997)	17.7(20.2)	0.79(0.75)	18.0(22.2)	15.4%	9
2014/2015	0.849(0.849)	27.1(30.4)	0.77(0.71)	23.6(27.4)	63.0%	7
2014/2015 (pre-melt)	1.12(1.31)	-8.38(-14.5)	0.55(0.60)	25.4(29.5)	42.4%	4
Combined	0.904(0.911)	27.5(31.0)	0.90(0.87)	23.1(27.4)	34.6%	19

Table 5: Regression coefficients and other statistical measures for the 2013/2014 intercomparison of the CS725 with manual SWE at Fortress Mountain (where β and ε are the slope and intercept of the regression line). Pre-Melt indicates that data occurring after maximum seasonal SWE is omitted from the analysis.

Season	β	ε mm w.e.	r^2	RMSE mm w.e.	Mean Relative Bias (K)	n
2013/2014	0.881	32.4	0.92	48.0	-4.5%	8
2013/2014 (pre-melt)	0.764	84.4	0.94	56.0	-3.6%	5

Figures

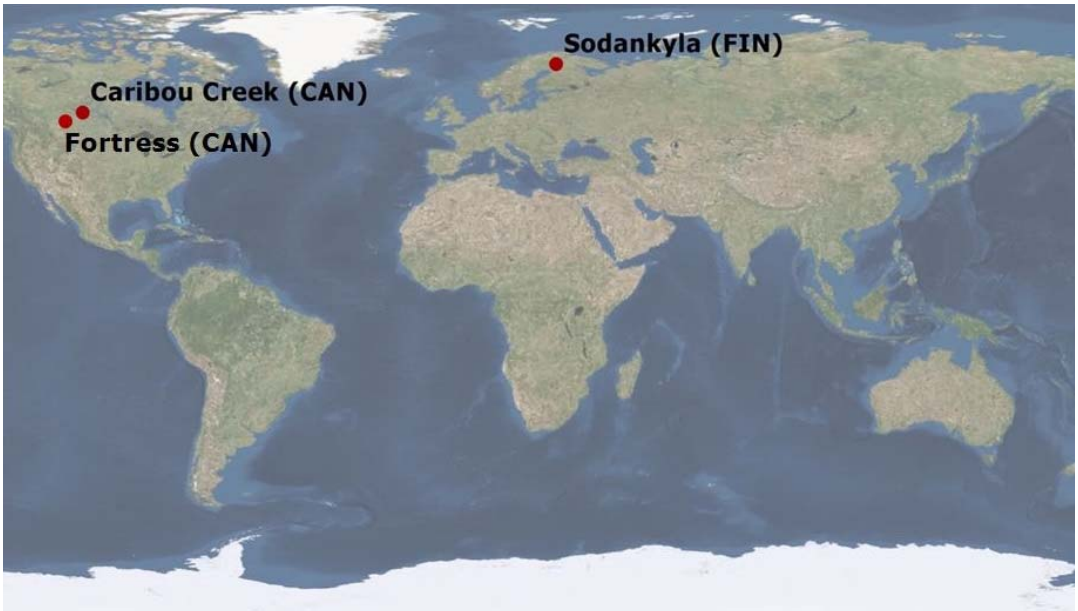

Figure 1: Location of the CS725 (Sodankylä, Caribou Creek, Fortress Mountain) and SSG1000 (Sodankylä) instrument installations.

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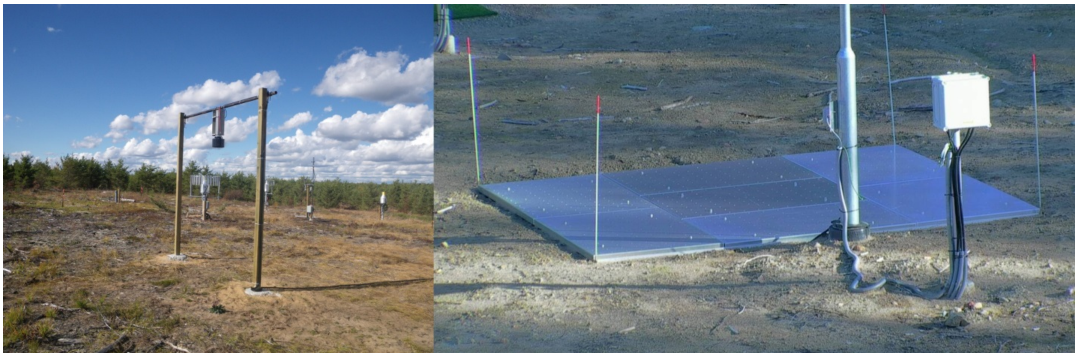

Figure 2: The Campbell Scientific CS725 (left) installed at Caribou Creek and the Sommer Messtechnik SSG 1000 (right) installed at Sodankylä.

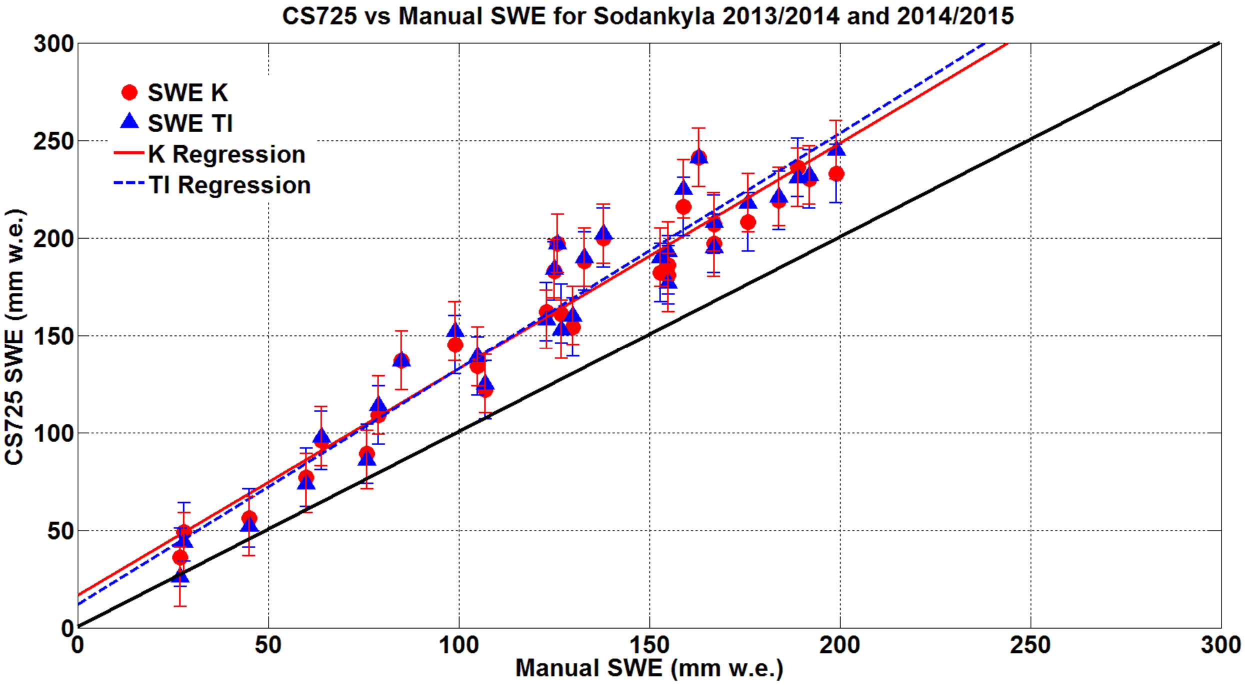

Figure 3: CS725 vs Manual SWE for Sodankylä for the 2013/2014 and 2014/2015 seasons (Potassium output or SWE K in red circles and solid red regression line and Thallium output or SWE Tl in blue triangles and dashed blue regression line). Black line is 1:1. Error bars represent the manufacturer's stated instrument accuracy.

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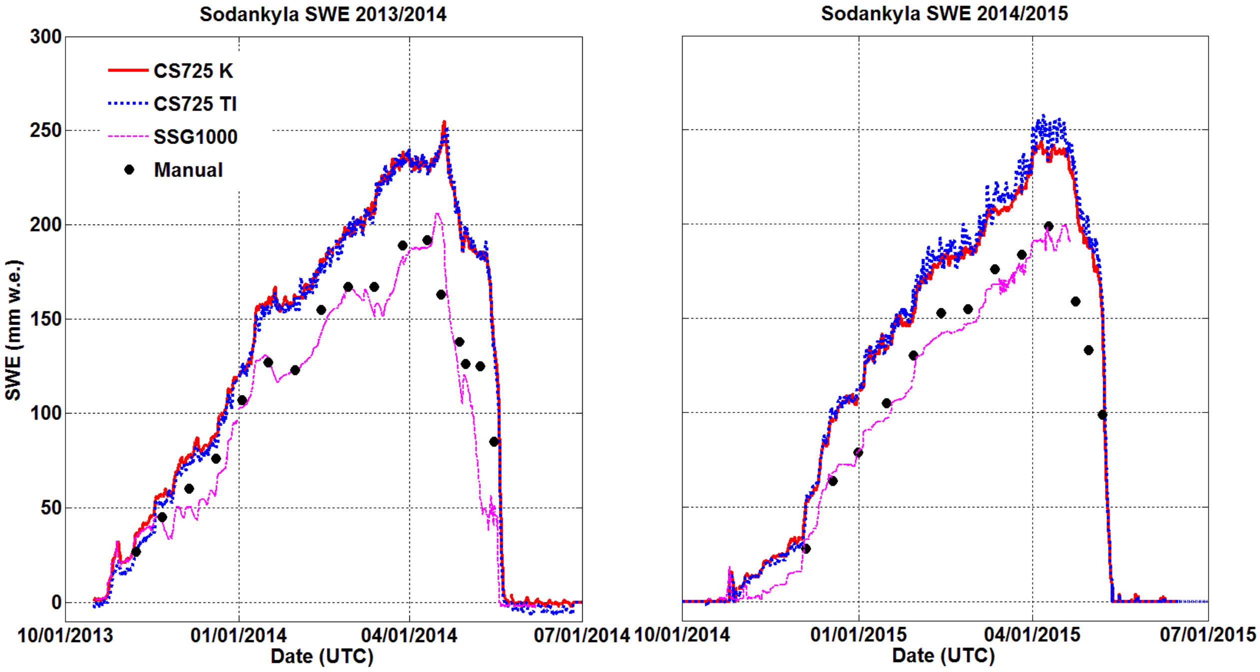

Figure 4: Time series of the SWE sensors (Potassium or CS725 K output in solid red, Thalium of CS725 Tl output in dashed blue, and SSG1000 output in dotted magenta) and manual SWE measurements at Sodankylä for the 2013/2014 (left) and 2014/2015 (right) seasons.

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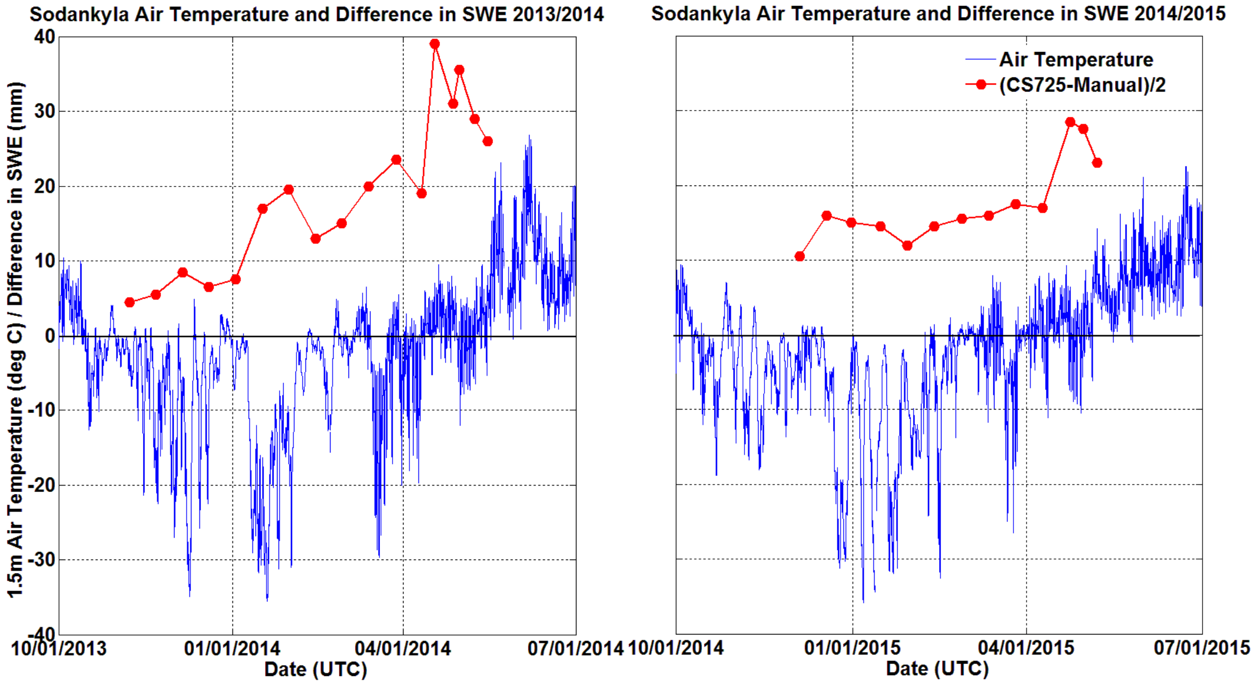

Figure 5: Time series of air temperature (blue) and the difference between CS725 and manual measurements (divided by 2, red) at Sodankylä for the 2013/2014 (left) and 2014/2015 (right) seasons.

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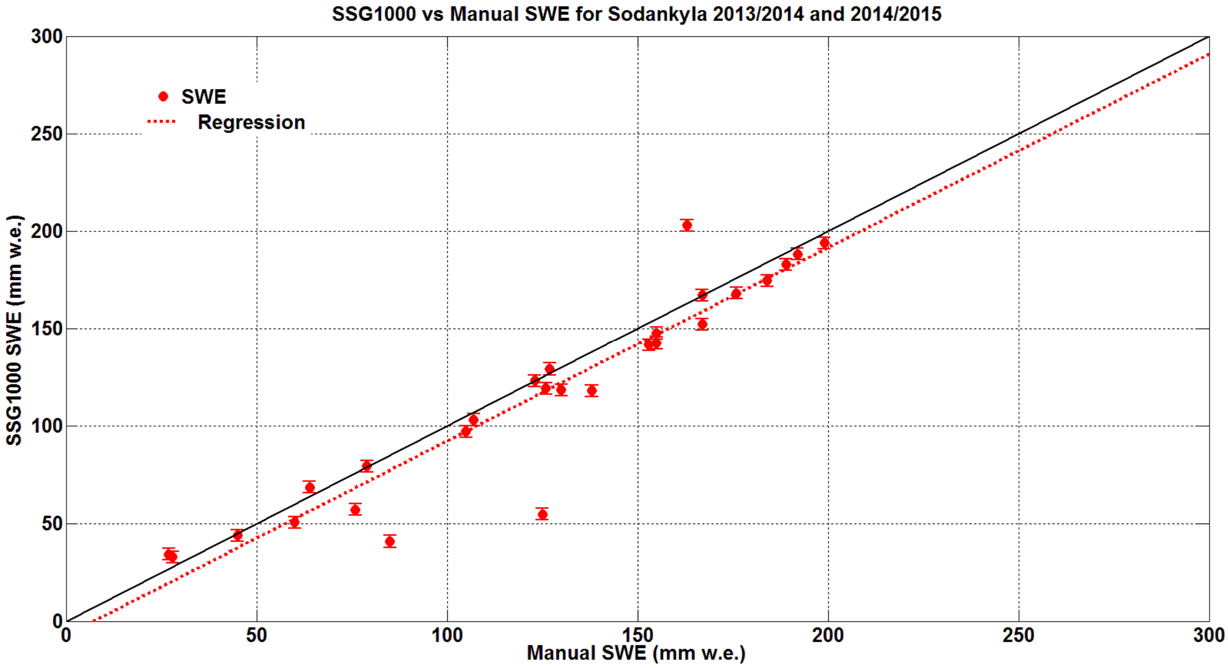

Figure 6: SSG1000 vs Manual SWE at Sodankylä for the 2013/2014 and 2014/2015 seasons. Black line is 1:1. Error bars represent the manufacturer's stated instrument accuracy.

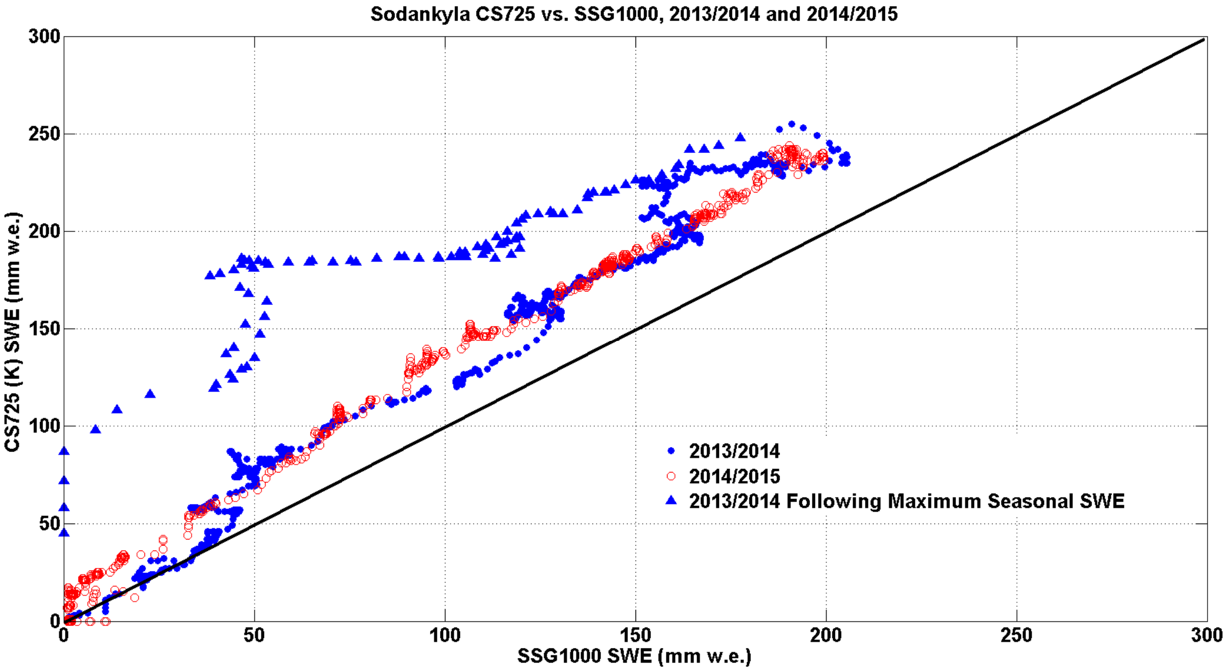

Figure 7: CS725 vs SSG1000 for the 2013/2014 (blue circles and triangles) and 2014/2015 (red unfilled circles) seasons at Sodankylä. Black line is 1:1. Blue triangles mark the 2013/2014 season after maximum seasonal SWE has been reached and melt has begun.

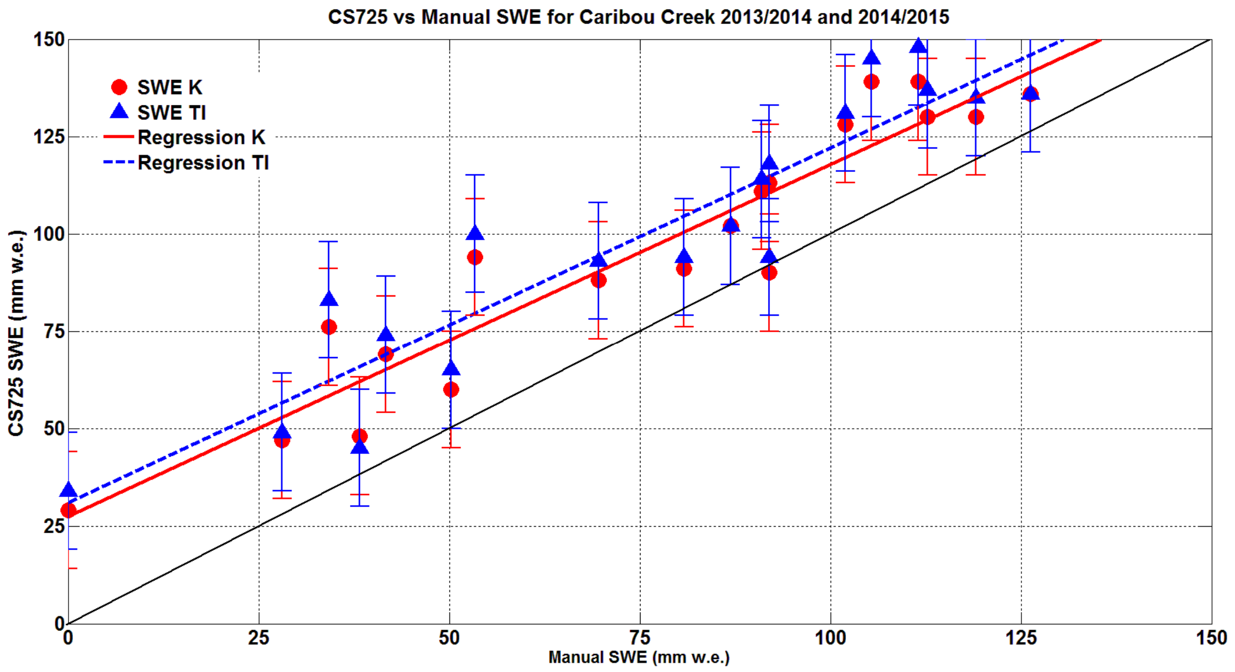

Figure 8: CS725 vs Manual SWE for Caribou Creek for the 2013/2014 and 2014/2015 seasons (Potassium or SWE K output in red circles and Thallium or SWE Tl output in blue triangles). Black line is 1:1. Error bars represent the manufacturer's stated instrument accuracy.

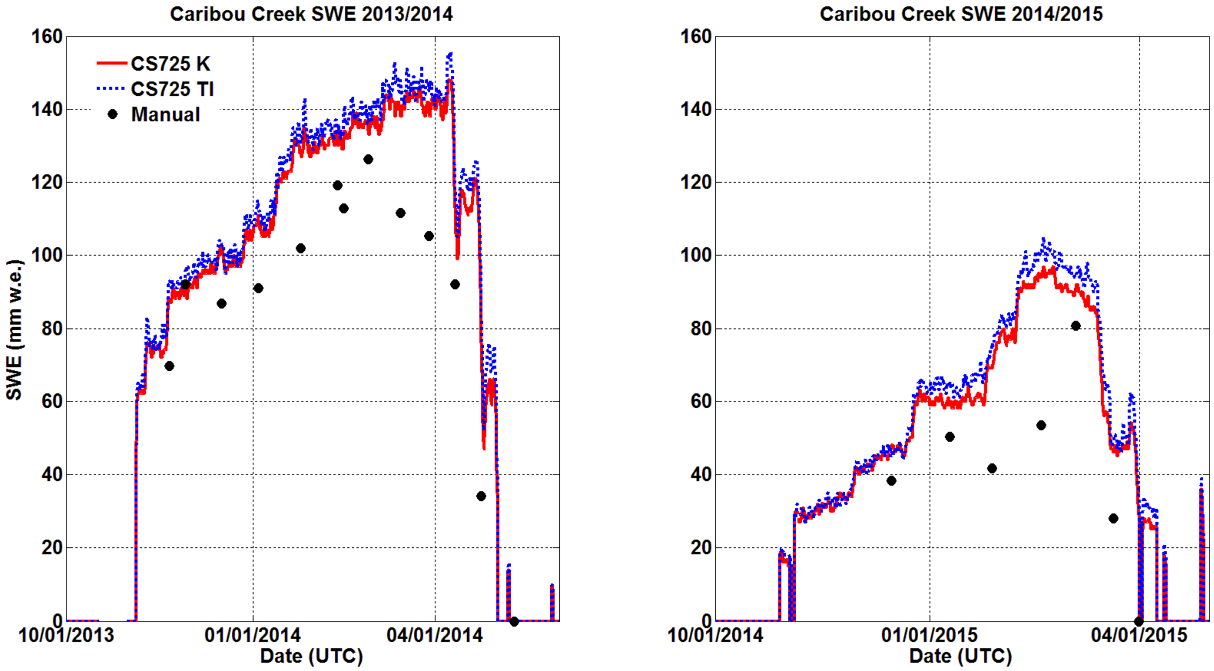

Figure 9: Time series of the SWE sensors (Potassium or CS725 K output in solid red and Thalium or CS725 Tl output in dashed blue) and manual SWE measurements at Caribou Creek for the 2013/2014 (left) and 2014/2015 (right) seasons.

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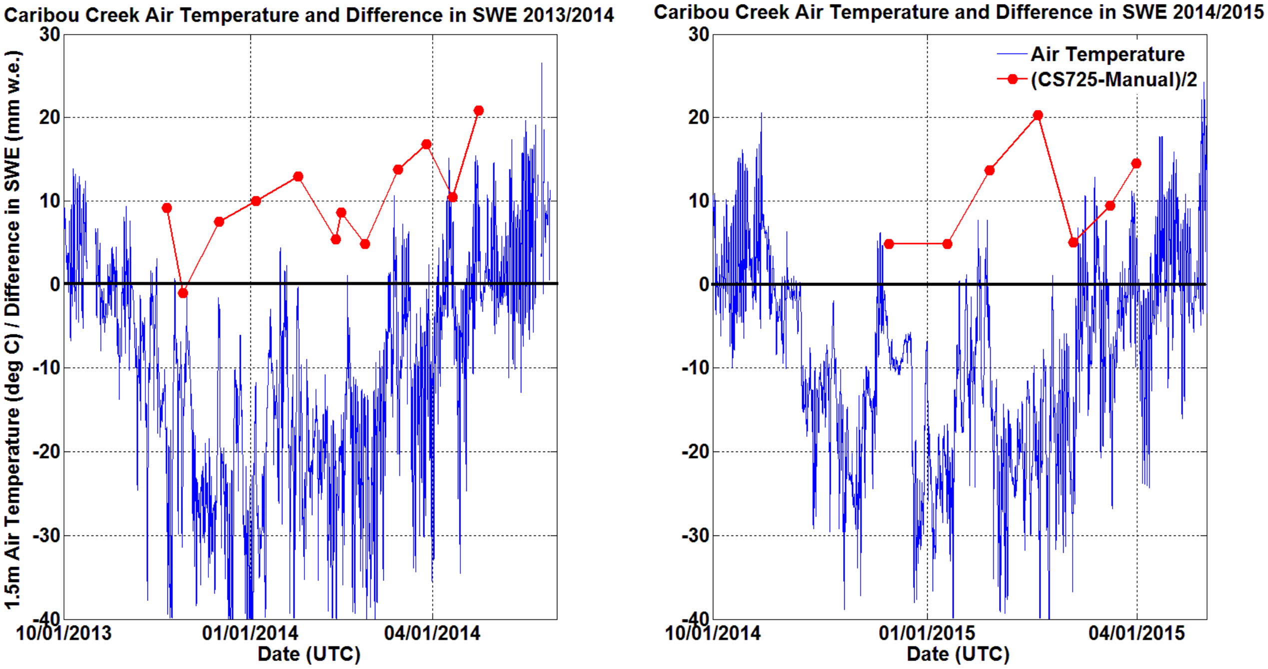

Figure 10: Time series of air temperature (blue) and difference between CS725 and manual measurements (divided by 2, red) at Caribou Creek for the 2013/2014 (left) and 2014/2015 (right) seasons.

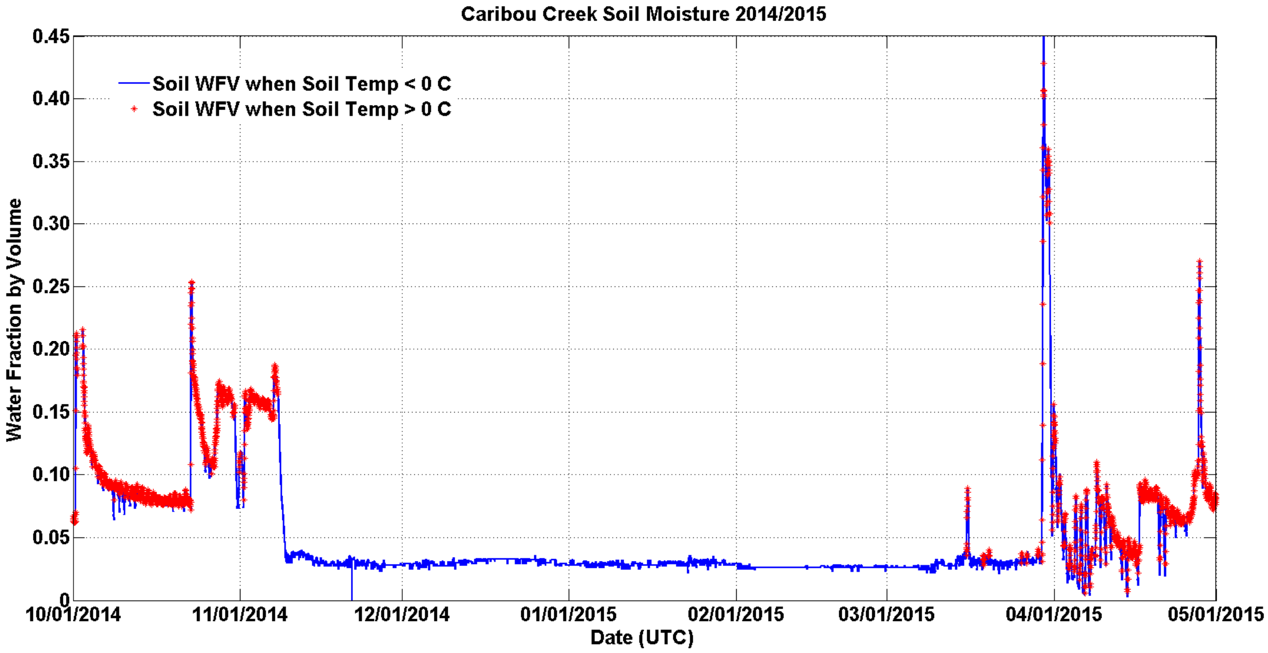

Figure 11: Time series of near surface (0 to 5 cm) soil moisture (water fraction by volume) at Caribou Creek for the 2014/2015 season. Red stars indicate where near surface soil temperature is above 0 °C.

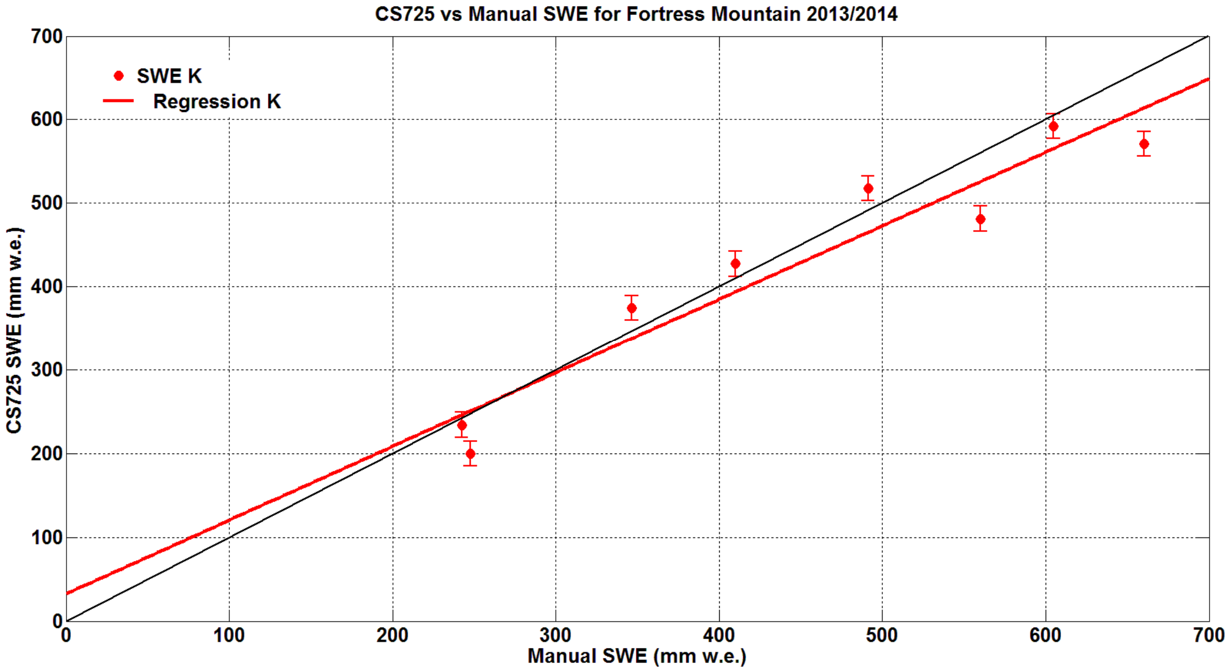

Figure 12: CS725 vs Manual SWE for Fortress Mountain for the 2013/2014 season (only Potassium or SWE K outputshown). Black line is 1:1. Error bars represent the manufacturer's stated instrument accuracy.

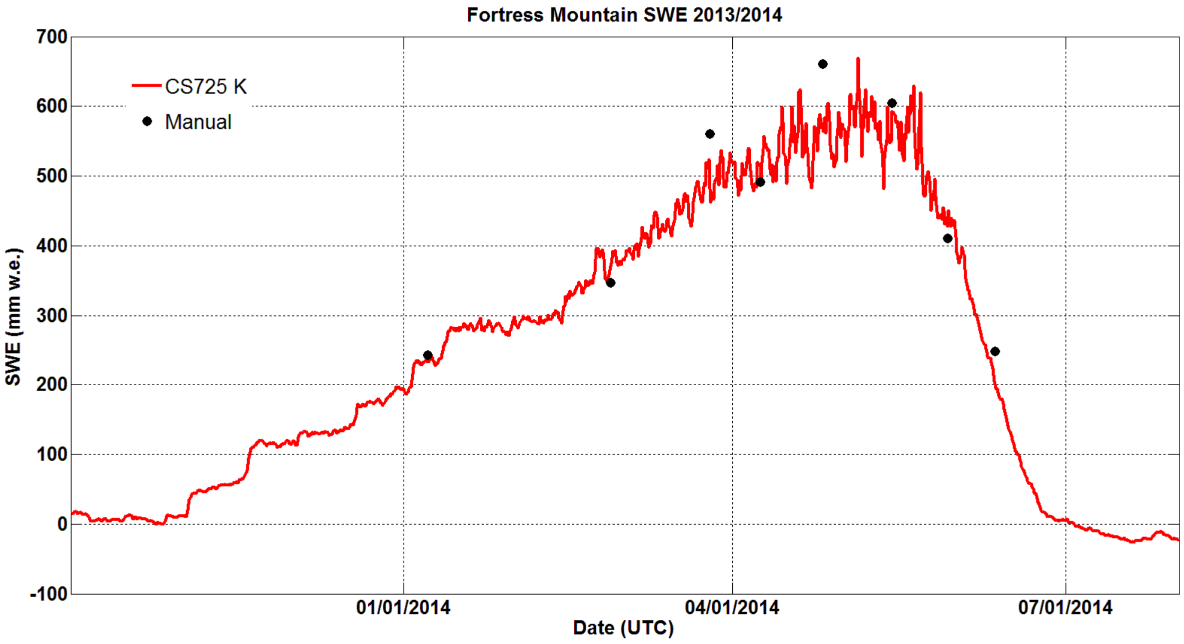

Figure 13: Time series of the SWE sensor and manual SWE measurements at Fortress Mountain for the 2013/2014 season.

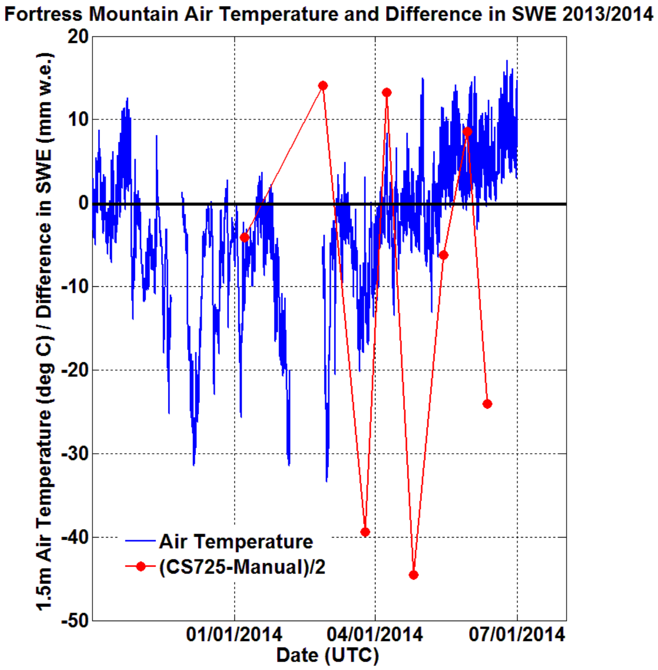

Figure 14: Time series of air temperature (blue) and difference between CS725 and Manual Measurements (divided by 2, red) at Fortress Mountain for the 2013/2014 season.