Review of

Snow data intercomparison on remote and glacierized high elevation areas (Forni Glacier, Italy)

The paper describes a method how to estimate SWE from automatic snow depth measurements at a high alpine site on a glacier during the accumulation phase. The method uses a fixed density for each daily positive snow depth difference to calculate the increasing SWE until its maximum. The method seems interesting and may have some potential.

My main criticism concerns the following important facts, which are missing:

- the exact determination of the fixed density
- the calculation of the daily positive snow depth differences
- the limitations and uncertainty of the method
- transferability to other sites and climates

The fixed density of 140 kg/m3 has already been used in earlier papers (2012, 2104) from you. Indeed the comparison between the estimated SWE from snow depth measurements and SWE from snow pits (the current Fig. 4) has already been published in The Cryosphere in 2014 (Fig. 2 in https://www.the-cryosphere.net/8/1921/2014/tc-8-1921-2014.pdf). However, there the estimated SWE data seem to be different from the one shown in the current paper? Can you explain?

Here a list of other important points, which need to be addressed before I can recommend accepting the paper for publication:

- Your fixed density is not a fresh snow density, since you totally neglect settling and are not able to determine small snow falls due to the measurement uncertainty of the snow depth sensor. The found density of 140 kg/m3 can therefore not be compared with published fresh snow densities found in literature and is relatively large since it has to compensate the missing snow fall amounts mentioned above.
- The impact of rain events at the beginning and end of the snow season has not been discussed so far.
- Since your focus is the determination SWE from snow depth your title needs to be changed to something like: Estimation of SWE from automatic snow depth measurements during accumulation on a high alpine glacier.
- The content of the abstract is odd. The abstract needs to be rewritten.
- The possible impact of the dislocation of the station needs to be discussed.
- You need to present some numbers about the uncertainty of the involved sensors, manual measurements and the uncertainty of the presented results. That means the papers definitely needs more quantitative information about the performance of your method.
- Information about the measurement frequency and aggregation of the data shown in the figures need to included.
- A comparison with data from other sites is needed in order to be able to judge the usefulness of the method.
- The English language of the paper is often odd and needs to be improved in revised version.

A list of minor comments and correction has directly been written in PDF of the paper below.

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Snow data intercomparison on ~~remote and~~ glacierized high elevation areas (Forni Glacier, Italy)

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Abstract.

We present and compare 11 years of snow data (snowfall, snow depth and snow water equivalent (*SWE*)) measured by an Automatic Weather Station and by some field campaigns on the Forni Glacier. The data have been acquired by means of i) a Campbell SR50 sonic ranger from October 2005 (snow depth data), ii) manual snow pits from January 2006 (snow depth and *SWE* data), iii) a Sommer USH8 sonic ranger from May 2014 (snow depth data), iv) a Park Mechanical SS-6048 snow pillow from May 2014 (*SWE* data), v) a manual snow weighting tube (Enel-Valtecne ©) from May 2014 (snow depth and *SWE* data). The aim of the analyses is to assess the mean value of fresh snow density and the most appropriate method to evaluate SWE for this measuring site.

The results indicate that the daily SR50 sonic ranger measures allow a rather good estimation of the *SWE*, and the provided snow pit data are available for defining the site mean value of fresh snow density. For the Forni Glacier measuring site, this value turned out to be 140 kg m^{-3}. The *SWE* derived from sonic ranger data is rather sensitive to this value: a change in fresh snow density of 20 kg m^{-3} causes a mean variation in *SWE* of ±0.093 m w.e. for each hydrological year, ranging from ±0.050 m w.e. to ±0.115 m w.e..

Keywords: Snow depth; Snow water equivalent (SWE); SPICE (Solid Precipitation Intercomparison Experiment) project; Forni Glacier.

1. Introduction and scientific background

The study of spatial and temporal variability of the water resource deriving from snow melt (i.e. Snow Water Equivalent, *SWE*) is very important for the estimation of the hydrological balance at catchment scale. In particular, many areas depend on this water reservoir for providing freshwater for civil use, irrigation and hydropower thus requiring an accurate and updated evaluation of *SWE* magnitude and variability. In addition, a correct *SWE* assessment also supports early strategies to manage and prevent hydro-meteorological risks (e.g. flood forecasting, avalanche forecasting).

In high mountain areas, however, only ~~snowfall~~ measures are often available: a correct evaluation of fresh snow density ($\rho_{fresh\ snow}$) is therefore needed to assess the SWE. Since fresh snow density is site specific and depending on atmospheric conditions, the main aim of this study is to investigate magnitude and rates of variations in $\rho_{fresh\ snow}$ and to understand how an incorrect assessment of this variable may affect the estimation of the SWE. This was possible by means of manual and automatic systematic measurements carried out at the surface of the Forni Glacier (Stelvio Park, Italian Alps, Fig. 1a and b). The Forni Glacier is a Site of Community Importance (SCI, code IT2040014) located inside a wide natural protected area (i.e. the Stelvio Park). It is a wide valley glacier (ca. 11.34 km^2 of area, D'Agata et al., 2014), covering an elevation range from 2600 to 3670 m a.s.l.. From 2005, an Automatic Weather Station (AWS1 Forni) has been acquiring snow data at the glacier surface in addition to measurements of snow depth and SWE by means of snow pits carried out by expert personnel (Citterio et al., 2007; Senese et al., 2012a; 2012b; 2014). The acquired snow data refer to snowfall or fresh-snow (i.e. depth of freshly fallen snow deposited over a specified period, generally 24 hours, see WMO, 2008) and to snow depth (i.e. the total depth of snow on the ground at the time of observation, see WMO, 2008). The long sequence of meteorological and glaciological data permitted the insertion of the AWS1 Forni into SPICE (Solid Precipitation Intercomparison Experiment) project managed and promoted by the WMO (World Meteorological Organization) and CryoNet project (core network of Global Cryosphere Watch promoted by the WMO).

Fresh snow-density assessment is important also for snowfall forecasting from orographic precipitation models (Judson and Doesken, 2000; Roebber et al., 2003), estimation of avalanche hazard (Perla, 1970; LaChapelle, 1980; Ferguson et al., 1990; McClung and Schaerer, 1993), snowdrift forecasting, as an input parameter in the snow accumulation algorithm (Super and Holroyd, 1997), and general snow science research.

Following Roebber et al. (2003), fresh snow density is often assumed to conform to the 10-to-1 rule: the snow ratio, defined by the density of water (1000 kg m^{-3}) to the density of fresh snow (assumed to be 100 kg m^{-3}), is 10:1. As noted by Judson and Doesken (2000), the 10-to-1 rule appears to originate from the results of a nineteenth-century Canadian study. More comprehensive measurements of fresh snow density (e.g., Currie, 1947; LaChapelle, 1962; Power et al., 1964; Super and Holroyd, 1997; Judson and Doesken, 2000) have established that this rule is an inadequate characterization of the true range of fresh snow densities. Indeed, they can vary from 10 kg m^{-3} to approximately 350 kg m^{-3} (Roebber et al., 2003). Bocchiola and Rosso (2007) report a similar range for the Central Italian Alps with values ranging from 30 kg m^{-3} to 480 kg m^{-3}, with an average sample value of 123 kg m^{-3}. Usually, the density of fresh snow is lower bounded to about 50 kg m^{-3} (Gray, 1979; Anderson and Crawford, 1990). Judson and Doesken (2000) found densities of fresh snow observed from six sheltered avalanche sites in the Central Rocky Mountains to range from 10 to 257 kg m^{-3} and average densities at each site based on four years of daily observations to range from 72 to 103 kg m^{-3}. Roebber et al. (2003) found that the 10-to-1 rule may be modified slightly to 12 to 1 or 20 to 1, depending on the mean or median climatological value of fresh snow density at a particular station (e.g. Currie 1947; Super and Holroyd, 1997). Following Pahaut (1975), the fresh snow density ranges from 20 to 200 kg m^{-3} and increases with wind speed and air temperature. Wetzel and Martin (2001) analyzed all empirical techniques evolved in the absence of explicit snow-density forecasts. As argued in Schultz et al. (2002), however, these techniques might be not fully adequate and the accuracy should be verified in details for a large variety of events.

Fresh snow density is regulated by i) in-cloud processes that affect the shape and size of growing ice crystals, ii) sub-cloud thermodynamic stratification through which an ice crystal falls (i.e. the low-level air temperature and relative humidity regulate the processes of sublimation or melting of a snowflake), and iii) ground-level compaction due to prevailing weather conditions and snowpack metamorphism. Understanding how these processes affect fresh snow density is difficult because direct observations of cloud microphysical processes, thermodynamic profiles, and surface measurements are often unavailable.

Cloud microphysical research indicates that many factors contribute to the final structure of an ice crystal. The shape of the ice crystal is determined by the environment in which the ice crystal grows: pure dendrites have the lowest density (Power et al., 1964), although the variation in the density of dendritic aggregates is large (from approximately 5 to 100 kg m^{-3}, Magono and Nakamura, 1965; Passarelli and Srivastava, 1979). Numerous observational studies over decades clearly demonstrate that the density varies inversely with size (Magono and Nakamura, 1965; Holroyd, 1971; Muramoto et al., 1995; Fabry and Szyrmer, 1999; Heymsfield et al., 2004; Brandes et al., 2007). The crystal size is related to the ratio between ice and air (Roebber et al., 2003): large dendritic crystals will occupy much empty air space, whereas smaller crystals will pack together into a denser assemblage. In addition, as an ice crystal falls, it passes through varying thermodynamic and moisture conditions. Then, the ultimate shape and size of crystals depend on factors that affect the growth rate and are a combination of various growth modes (e.g. Pruppacher and Klett, 1997).

To contribute to the understanding of all the above topics, in this paper we discus and compare all the available snow data measured at the Forni Glacier surface in the last decade to: i) suggest the most suitable measurement method to evaluate *SWE* at a glacier surface (i.e. snow pillow or sonic ranger or snow pits); ii) define the reliability of the obtained *SWE* values and their accuracies; iii) check the validity of the $\rho_{fresh\ snow}$ value previously found (i.e. 140 kg m^{-3}, see Senese et al., 2014) to support *SWE* computation; and iv) evaluate effects and impacts of uncertainties in the $\rho_{fresh\ snow}$ value in the derived *SWE* amount.

2. Data and Methods

Snow data at the Forni Glacier have been acquired by means of i) a Campbell SR50 sonic ranger from October 2005 (snow depth data), ii) manual snow pits from January 2006 (snow depth and *SWE* data), iii) a Sommer USH8 sonic ranger from May 2014 (snow depth data), iv) a Park Mechanical SS-6048 snow pillow from May 2014 (*SWE* data), v) a manual snow weighting tube (Enel-Valtecne ©) from May 2014 (snow depth and *SWE* data). These sensors are installed at two automatic weather stations (AWSs): AWS1 Forni and AWS Forni SPICE. The first station (named AWS1 Forni, Fig. 1b) was installed on 26th September 2005 at the lower sector of the Forni Glacier eastern tongue (Citterio et al., 2007; Senese et al., 2012a, 2012b; 2014; 2016). The WGS84 coordinates of AWS1 Forni are: 46° 23’ 56.0” N, 10° 35’ 25.2” E, 2631 m a.s.l. (Fig. 1a, yellow triangle).The second station (named AWS Forni SPICE, Fig. 1b) was installed on 6th May 2014 close to the AWS1 Forni (at a distance of 17 m).

The AWS1 Forni is equipped with sensors for measuring air temperature and humidity (naturally ventilated sensor), wind speed and direction, air pressure, and the four components of the radiation budget (longwave and shortwave, both incoming and outgoing fluxes), liquid precipitation, and snow depth by means of the Campbell SR50 sonic ranger (Table 1, see also Senese et al., 2012a).

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The AWS Forni SPICE is equipped with sensors for measuring also the snow water equivalent by means of the snow pillow and the air pressure (Table 1). This latter permits to calibrate the output values recorded by the snow pillow. The pressure snow pillow gauge is a device similar to a large air or water mattress filled with antifreeze. As snow is deposited on this gauge, the pressure increase is related to the accumulating mass and thus to *SWE*. On the mast, an automated camera was installed to photograph four graduated stakes located at the corners of the snow pillow (Fig. 1b). When the snow pillow was installed, a second sonic ranger (Sommer USH8) was installed on the AWS1 Forni.

The main constrictions in installing and managing AWS1 Forni and AWS Forni SPICE were due to the fact that the site is located on the surface of an Alpine glacier, not always accessible, especially during wintertime when skis and skins are needed on the steep and narrow path, and avalanches can occur. Moreover, the glacier is a dynamic body (moving up to 20-30 m y^{-1}, Urbini et al., 2017) and its surface also features a well-developed roughness due to ice melting, flowing meltwater, differential ablation and opening crevasses (Diolaiuti and Smiraglia, 2010; Smiraglia and Diolaiuti, 2011). In addition, the power to be supplied to instruments and sensors is only represented by solar panels and lead-gel batteries. Then, a deep and accurate analysis of instruments and devices (i.e. energy supply required, performance and efficiency working at low temperatures, noise in measuring due to ice flow, etc.) before their installation on the supraglacial AWS is necessary to avoid interruptions in data acquisition and storage.

As regards the AWS1 Forni, two data loggers are installed: a LSI-Lastem Babuc ABC (in 2005) and a Campbell Scientific CR200 (in 2014). This latter allows the correct working of the Young wind sensor and the Sommer sonic ranger. All the other sensors are connected to the LSI-Lastem Babuc ABC. A Campbell Scientific CR1000 was installed at the AWS Forni SPICE (in 2014).

The whole systems of both AWS1 Forni and AWS Forni SPICE are supported by four-leg stainless steel masts (5 m and 6 m high, respectively) standing on the ice surface. In this way, the AWSs stand freely on the ice, and adjust to the melting surface during summer.

Due to the formation of ring faults that could compromise the stability of the stations (Azzoni et al., submitted), in November 2015 both AWSs were moved to the Forni glacier central tongue (46°23'42.40"N and 10°35'24.20"E at an elevation of 2675 m a.s.l., the red star in Fig. 1a).

In addition, since winter 2005/2006, personnel from the Centro Nivo-Meteorologico (namely CNM Bormio-ARPA Lombardia) of the Lombardy Regional Agency for the Environment have been carrying out periodic snow pits (performed according to the AINEVA protocol, see also Senese et al., 2014) in order to estimate snow depth and *SWE*. In particular, the thickness (h_i) and the density (ρ_i) of each snow layer (i) are measured for estimating the snow water equivalent of each layer and then the total $SWE_{snow-pit}$ of the whole snow cover (n layers):

$$SWE_{snow-pit} = \sum_{i=1}^{n} h_i \cdot \frac{\rho_i}{\rho_{water}} \quad (1)$$

where ρ_{water} is density of water. As stated in a previous study (Senese et al., 2014), the date when the snow pit is dug is very important for not underestimating the actual accumulation. For this reason, we considered only the snow pits carried out before the beginning of snow ablation. In fact, whenever ablation occurs, successive *SWE* values derived from snow pits show a decreasing trend (i.e. they are affected by mass losses). In these cases, we considered the highest SWE value, before the occurrence of snow ablation.

SWE values are also estimated from snow depth data acquired by sonic rangers. In particular, daily positive differences in depth (Δh) are considered:

$$SWE_{sonic-ranger} = \sum_{t=1}^{m}(\Delta h_t)\cdot\frac{\rho_{fresh\ snow}}{\rho_{water}} \qquad (2)$$

where *m* is the total number of snow days and $\rho_{fresh\ snow}$ is the fresh snow density.

The optimal value of $\rho_{fresh\ snow}$ is then found by comparing *SWE* from sonic rangers (where fresh snow density is the unique unknown parameter but the record of data is generally continuous and uninterrupted thus recording all the snowfall events) against *SWE* from snow pits (where snow density is sampled at each layer but these measurements are performed in a unique date).

In previous analyses performed using Forni Glacier data, we have obtained the best match against the two data series by applying a $\rho_{fresh\ snow}$ value of 140 kg m^{-3} (see Citterio et al., 2007; Senese et al., 2012a; 2014).

3. Results

Figure 2 represents the 11-year dataset of snow depth measured by the sonic ranger SR50 from 2005 to 2016. The last data (after October 2015) were recorded in a different site than the previous one because of the AWSs displacement of November 2015.

A large interannual variability is seen with the maximum peak of 2.80 m (on 2nd May ~~2008~~). In general, the snow depth exceeds 2 m, except in 2006-2007 period, which is characterized by the lowest maximum value (1.34 m on 26th March 2007).

The snow accumulation period generally starts between the end of September and the beginning of October. Whereas, the snow appears to be completely melted between the half of June and the beginning of July (Fig. 2).

During the last two years, data from the sonic ranger Sommer USH8 were also available even if with some gaps (26% of the total period). Comparing the datasets from Campbell and Sommer sensors, a very good agreement is found (Fig. 3). This means that in spite of some problems in recording Sommer sonic ranger data, both sensors worked correctly and all the snowfalls were properly recognized.

Because of the not complete dataset from the sonic ranger Sommer USH8, the following analyses are however performed considering only the Campbell SR50 sensor.

Figure 4 reports the comparison between the sonic ranger-derived *SWE* values (i.e. applying Eq. (2) and using a fresh snow density of 140 kg m^{-3}) and the ones obtained by snow pits from 2005 to 2016. As found in previous studies (Senese et al., 2012a, 2014), there is a very good agreement between the two series of data (i.e. snow-pit-measured and sonic-ranger-derived *SWE*). Whenever sonic ranger data are not available for a long period, the derived total *SWE* value results to be incorrect. In particular, it is clear that the period of the year without data is very important for not underestimating the actual accumulation. During the snow accumulation period 2010-2011, the data gap from 15 December 2010 to 12 February 2011 (totally 60 days) produces an underestimation of 0.163 m w.e. (on 25th April 2011 derived *SWE* = 0.607 and measured *SWE* = 0.770, Fig. 4). During the hydrological years 2011-2012 and 2012-2013, there were some problems with sonic ranger data acquisition thus making impossible to elaborate these data from 31st January 2012 to 25th April 2013. In these cases, there are noticeable differences between the two series of data: on 1st May 2012 measured *SWE* = 0.615 m w.e. and derived *SWE* = 0.238 m w.e., and on 25th April 2013 measured *SWE* = 0.778 m w.e. and derived *SWE* = 0.307 m w.e., Fig. 4). ~~Therefore, whenever the recorded data are not available from February, the derived *SWE* could not be considered adequate and generally equal to the half of the total value.~~

Figure 5 reports the comparison between the sonic ranger-derived SWE values and the ones obtained by the snow pillow (2014-2016 period). From this graph, it is evident that the snow pillow has some measuring problems at the beginning of the snow season when snow cover is low. Except this first period without snow, the curve of *SWE* measured by the snow pillow follows the sonic ranger-derived SWE curve (Fig. 5), thus suggesting a correct working of the sensor. In order to better assess the reliability of our derived *SWE* values, a scatter plot of measured versus derived *SWE* data is shown (Fig. 6). The chosen period is the snow accumulation time frame during 2014/2015 and 2015/2016: from November 2014 to March 2015 and from February 2016 to May 2016 (i.e. excluding the initial period in which the snow pillow seems to have relevant measuring problems, to the moment before the beginning of snow ablation, see Fig 3). There is a general underestimation of derided *SWE* from SR50 compared to the ones measured by both snow pillow and snow pit considering data of 2014/2015, however the agreement raises with 2015/2016 dataset (Fig. 6). The root mean square error is 0.051 m w.e. if compared with snow pillow dataset, and the difference with the snow pit is 0.067 m w.e. Nevertheless, carrying out numerous measurements through the snow weighting tube (Enel-Valtecne ©) around the AWSs on 20th February 2015, a large spatial variability of snow depth was found even if the snow surface seemed to be homogenous. This was mainly due to the roughness of the glacier ice surface. Indeed, on 20th February 2015 the snow pillow recorded a *SWE* value of 0.493 m w.e., while from the snow pit the *SWE* resulted equal to 0.555 m w.e., and from the snow weighing tube the *SWE* ranged from 0.410 to 0.552 m w.e., even if all measurements were performed very close to each other. In addition, this difference can be also due to oversampling by the snow tube (Work et al., 1965).

4. Discussions

Once verified our procedure, we performed further tests in order to define the *SWE* sensitivity with changing the fresh snow density (Fig. 7). An increase/decrease of 20 kg m^{-3} causes a mean variation in *SWE* of ±0.093 m w.e. for each hydrological year, ranging from ±0.050 m w.e. to ±0.115 m w.e. From this analysis, using a density value of 140 kg m^{-3} is confirmed to be the best one compared with *SWE* values measured by snow pits (Table 2).

Beside to a general good agreement between the measures performed with the different sensors, there are also some problems. Focusing only on the beginning of the snow accumulation period, it appears that all sensors (i.e. sonic ranger and snow pillow) are not able to correctly detect the first snowfall events. As regards sonic ranger, the surface roughness of the glacier ice does not allow to distinguish a few centimeters of fresh snow, as it causes differences in surface elevation up to tens of centimeters and affects the angular distribution of reflected ultrasound. At 3 m of height, the diameter of measuring field is 1.17 m and 0.63 m for SR50 and USH8, respectively. For these reasons, the sonic ranger generally records not constant distances between ice surface and sensor. This issue does not occur with thick snow cover as the snow roughness is very small compared to the ice one. In order to assess the beginning of the snow accumulation period, albedo represents a useful tool as fresh snow and ice are characterized by very different values (e.g. Azzoni et al., 2016). In fact, whenever a snowfall event occurs, albedo immediately raises from about 0.2 to 0.9 (typical values of ice and fresh snow, respectively, Senese et al., 2012a). This is confirmed also by the pictures taken hourly by the AWSs automated camera. During the hydrological year 2014/2015, the first snowfall was detected on 22nd October 2014 by analyzing albedo data and it is verified by pictures taken by the automated camera. Before this date, the sonic ranger does not recorded a null snow depth mainly due to the ice roughness and then we had to correct the dataset accordingly.

Regarding snow pillow, some of the under-measurement or over-measurement errors can be attributed to differences in the amount of snow settlement over the snow pillow compared with the surrounding ground, or to bridging over the snow pillow with cold conditions during development of the snow cover (Beaumont, 1965). The dominant source of *SWE* snow pillow errors is generally due to measuring problems of this device, which is sensitive to the thermal conditions of the sensor, the ground and the snow (Johnson et al., 2015). In fact, according to Johnson and Schaefer (2002) and Johnson (2004) snow pillow under-measurement and over-measurement errors can be related to the amount of heat conduction from the ground into the overlying snow cover, the temperature at the ground/snow interface and the insulating effect of the overlying snow. Analyzing 2014/2015 and 2015/2016 data, the snow pillow seems to be working correctly only with snow cover thicker than 50 cm (Fig. 5).

~~In general, the precipitation can be acquired mechanically, optically, in capacitive way and by means of radar. Some examples of available sensors are: heated tipping bucket rain gauge (as precipitation is collected and melted in the gauge's funnel, water is directed to a tipping bucket mechanism adjusted to tip and dump when a volume threshold of water is collected), heated weighing gauge (the weight of water collected is measured as a function of time and converted to rainfall depth), disdrometer (measuring the drop size distribution and velocity of falling hydrometeors), snow water equivalent sensor based on the attenuation of the electromagnetic energy from the ground (by passively detecting the change in naturally occurring electromagnetic energy from the ground after it passes through snow cover). In particular, for the Solid Precipitation Intercomparison Experiment (1989-1993), the International Organizing Committeee designated the following method as the reference for the Intercomparison and named it as the Double Fence Intercomparison Reference (DFIR): "The octagonal vertical double-fence inscribed into circles 12 m and 4 m in diameter, with the outer fence 3.5 m high and the inner fence 3.0 m high surrounding a Tretyakov precipitation gauge mounted at a height of 3.0 m. In the outer fence there is a gap of 2.0 m and in the inner fence of 1.5 m between the ground and the bottom of the fences." (WMO/TD-872/1998, section 2.2.2). In remote areas like a glacier, it is however very difficult to install and maintain such sensors. One of the constrictions concerns the power to be supplied to instruments that is represented only by solar panels and lead-gel batteries. In fact, at the Forni site we had to choose only unheated low-power sensors.~~ The snow pillow turned out to be logistically unsuitable, as it required frequent maintenance. Especially with bare ice or few centimeters of snow cover, the differential ablation causes instability of the snow pillow mainly due to its size. In addition, it is not able to detect *SWE* lower than about 0.2 m w.e. (corresponding to a snow depth of about 50 cm). Therefore, this sensor is resulted to be a tool not appropriate for a glacier surface or a remote area in general. The snow pit can represent a useful approach but it requires expert personnel for carrying out the measurement. Moreover, as discussed in Senese et al. (2014), it is very important to select a correct date for performing snow pits in order to assess the whole glacier accumulation amount. Generally, 1st April is the date largely considered as the most indicative of the cumulative *SWE* in high mountain environments of the midlatitudes, but this date is not always the best one. In fact, Senese et al. (2014) found that using a fixed date for measuring the total *SWE* is not the most suitable solution. In particular, they suggest that a correct temperature threshold can help in detecting the most appropriate time window of analysis indicating the starting time of snow melting processes and then the end of the accumulation period. The automated camera provided hourly photos but for assessing a correct snow depth at least two graduated rods have to be installed closed to the automated camera. Over a glacier surface, glacier dynamics and snow flux can compromise the stability of the rods: in fact, after a short while we found them broken at the AWS Forni SPICE. Finally, with data acquired by the SR50 sonic ranger a correct curve of *SWE* was derived. ~~The unique issue is represented by the definition~~ of the beginning of the accumulation period, but this can be overcome using albedo data. Unlike SR50 sensor, USH8 sonic ranger showed more problems and then less available data that did not make possible to calculate *SWE* values. Therefore, SR50 sonic ranger turned out to be the most suitable device in order to define both snow depth and daily cumulative *SWE* (as the fresh snow density is defined).

5. Conclusions

In occasion of the SPICE (Solid Precipitation Intercomparison Experiment) project, at the Forni Glacier (Italian Alps) snow measurements have been carried out by means of several automatic and manual approaches from 2014. This has allowed an accurate comparison and evaluation of pros and cons in using snow pillow or sonic ranger or manual snow pit and snow weighting tube. The results achieved during the SPICE experiment support our procedure for deriving *SWE* values and the applied fresh snow density of 140 kg m^{-3} (Senese et al., 2014), and suggest that, once $\rho_{fresh\ snow}$ is known, the SR50 sonic ranger can be considered the most suitable device on a glacier to record snowfall events and to measure snow depth values in order to derive the point SWE. Moreover, we evaluated effects and impacts of changing $\rho_{fresh\ snow}$ value in the derived *SWE* amount and we found that a slight change in density of 20 kg m^{-3} causes a mean variation in *SWE* of ±0.093 m w.e. for each hydrological year, ranging from ±0.050 m w.e. to ±0.115 m w.e.

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379 Table 1: Instrumentation at the Forni Glacier with instrument name, measured parameter, manufacturer, and starting date.

Instrument name	**Parameter**	**Manufacturer**	**Date**
Babuc ABC	Data logger	LSI LASTEM	Sept. 2005
CR200	Data logger	Campbell	May 2014
CR1000	Data logger	Campbell	May 2014
Sonic ranger SR50	Snow depth	Campbell	Sept. 2005
Sonic ranger USH8	Snow depth	Sommer	May 2014
Snow pillow	SWE	Park Mechanical Inc.	May 2014
Thermo-hygrometer	Air temperature and humidity	LSI LASTEM	Sept. 2005
Barometer	Atmospheric pressure	LSI LASTEM	Sept. 2005
Net Radiometer CNR1	Short and long wave radiation fluxes	Kipp & Zonen	Sept. 2005
Pluviometer unheated	Liquid precipitation	LSI LASTEM	Sept. 2005
Anemometer 05103V	Wind speed and direction	Young	Sept. 2005

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Table 2: For each snow pit measurement, *SWE* values (in m w.e.) are reported. The values are obtained by applying fresh snow density ranging from 100 to 180 kg m^{-3}. In the last column is reported the value measured by snow pits.

	100	**120**	**140**	**160**	**180**	**Snow pit**
24/01/06	0.229	0.275	0.321	0.367	0.413	0.337
02/03/06	0.335	0.402	0.469	0.536	0.603	0.430
30/03/06	0.421	0.505	0.589	0.673	0.757	0.619
07/05/08	0.492	0.590	0.688	0.787	0.885	0.690
21/02/09	0.427	0.513	0.598	0.684	0.769	0.650
27/03/10	0.410	0.492	0.573	0.655	0.737	0.640
25/04/11	0.530	0.636	0.742	0.848	0.953	0.770
01/05/12	0.437	0.525	0.612	0.700	0.787	0.615
25/04/13	-	-	-	-	-	0.778
06/05/14	0.337	0.404	0.472	0.539	0.607	1.043
20/02/15	0.363	0.436	0.508	0.581	0.653	0.555

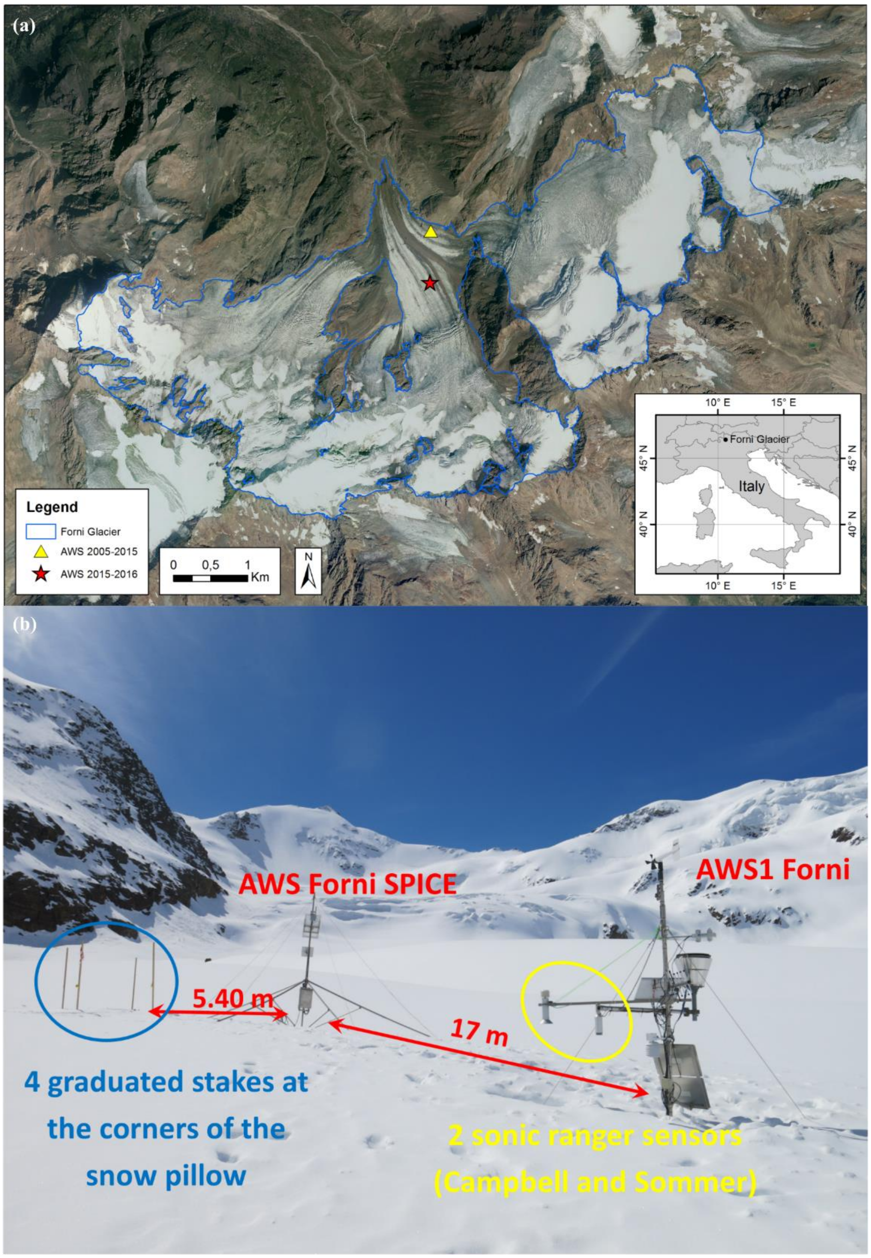


Figure 1: (a) The study site. The yellow triangle indicates the location of the AWS1 Forni and the Forni AWS SPICE until November 2015. The red star refers to the actual location after securing the stations. (b) AWS1 Forni (on the right) and AWS Forni SPICE (on the left) photographed from the North-East on 6th May 2014 (immediately after the installation of the AWS Forni SPICE). The distances between the stations are shown.

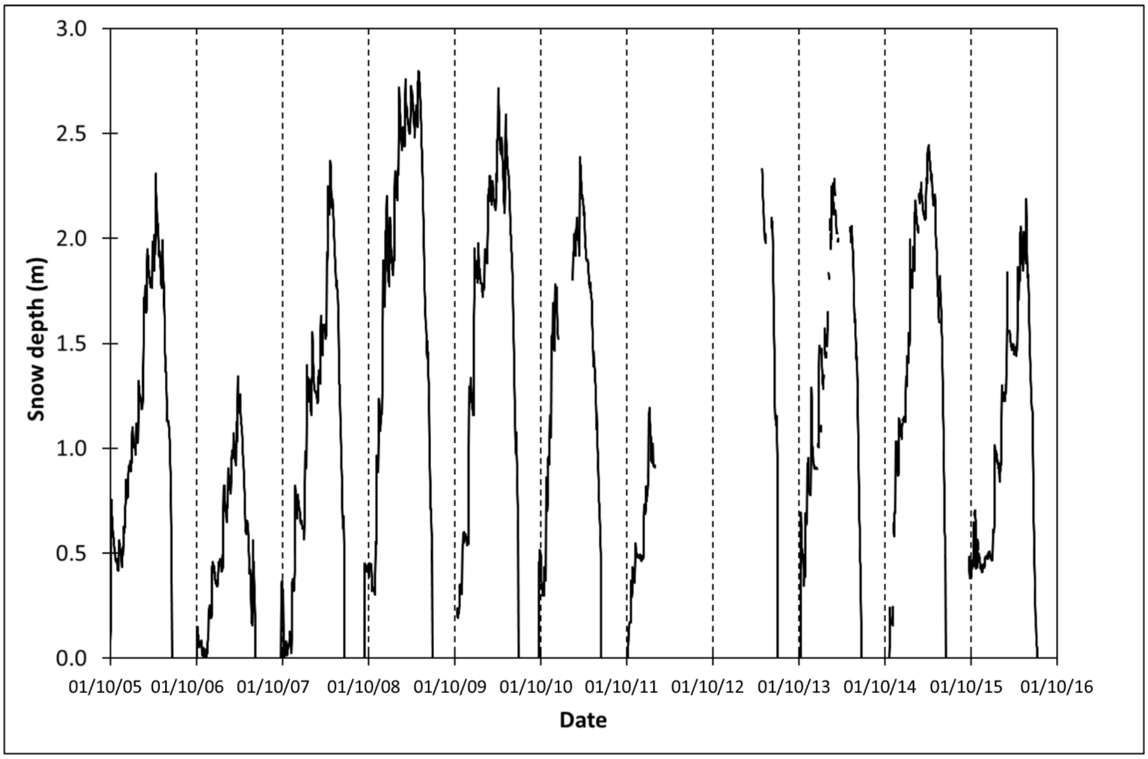
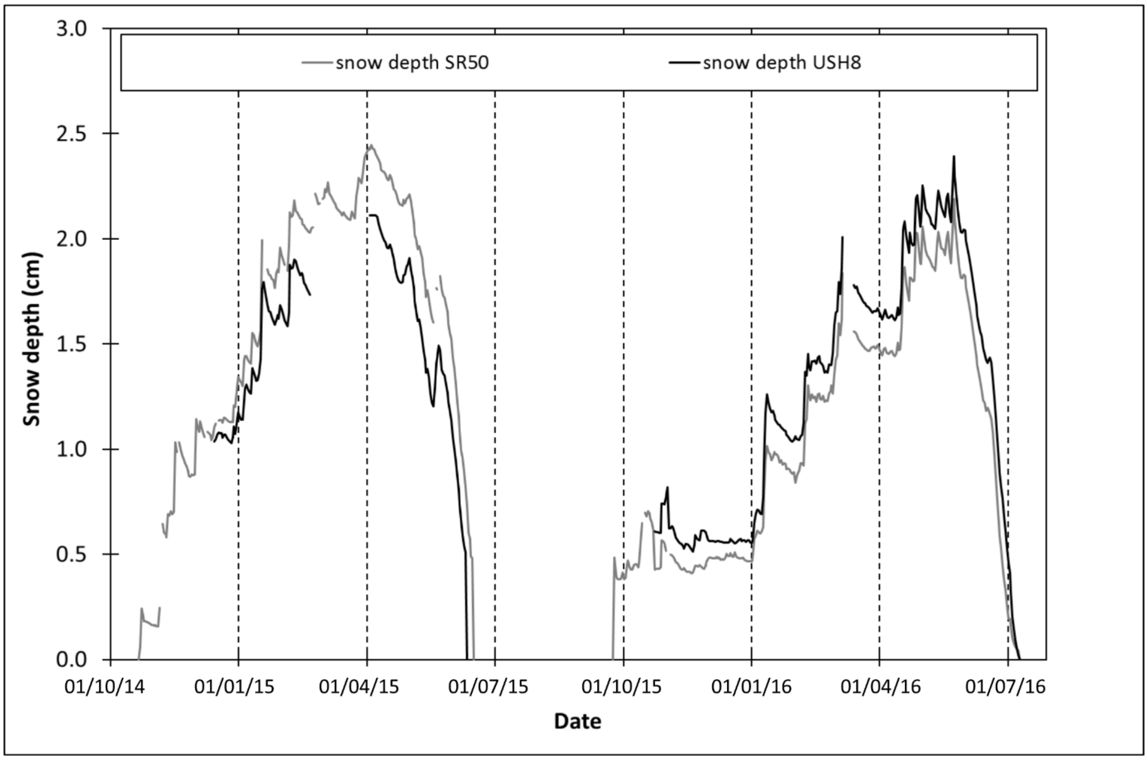


Figure 2: Snow depth measured by the Campbell SR-50 sonic ranger at the AWS1 Forni from 1st October 2005 to 30th September 2016. The dates shown are dd/mm/yy.



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396 **Figure 3: Snow depth data measured by Campbell SR50 and Sommer USH8, from October 2014 to July 2016. The**

397 **dates shown are dd/mm/yy.**

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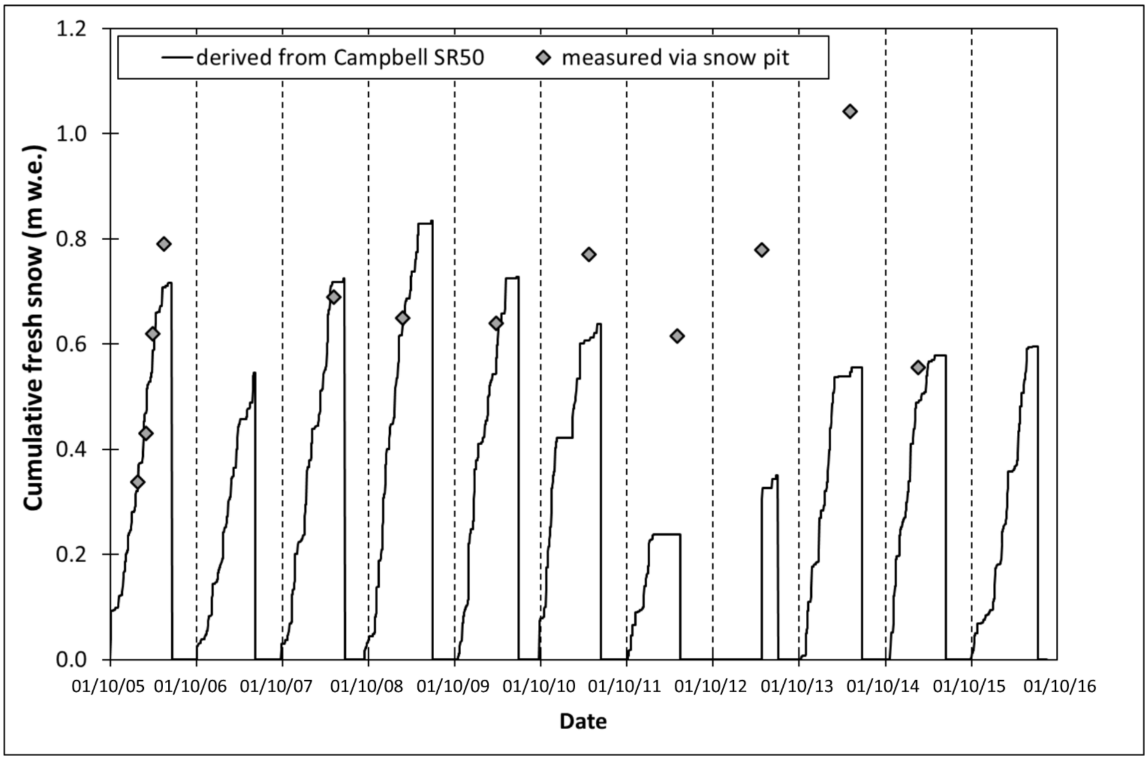

Figure 4: *SWE* data derived from snow depth by the Campbell SR50 and measured by snow pits from 1st October 2005 to 30th September 2016. The dates shown are dd/mm/yy.

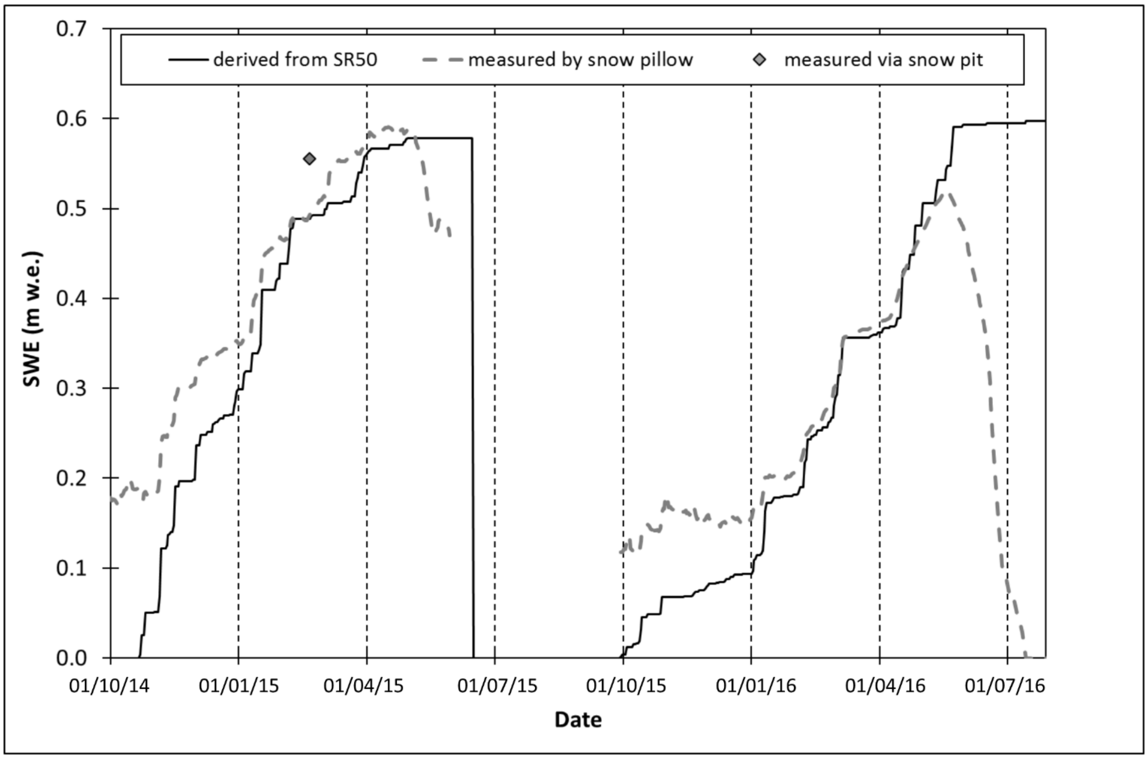

Figure 5: SWE data derived from snow depth measured by Campbell SR50 and measured by snow pits and snow pillow from October 2014 to July 2016. The dates shown are dd/mm/yy.

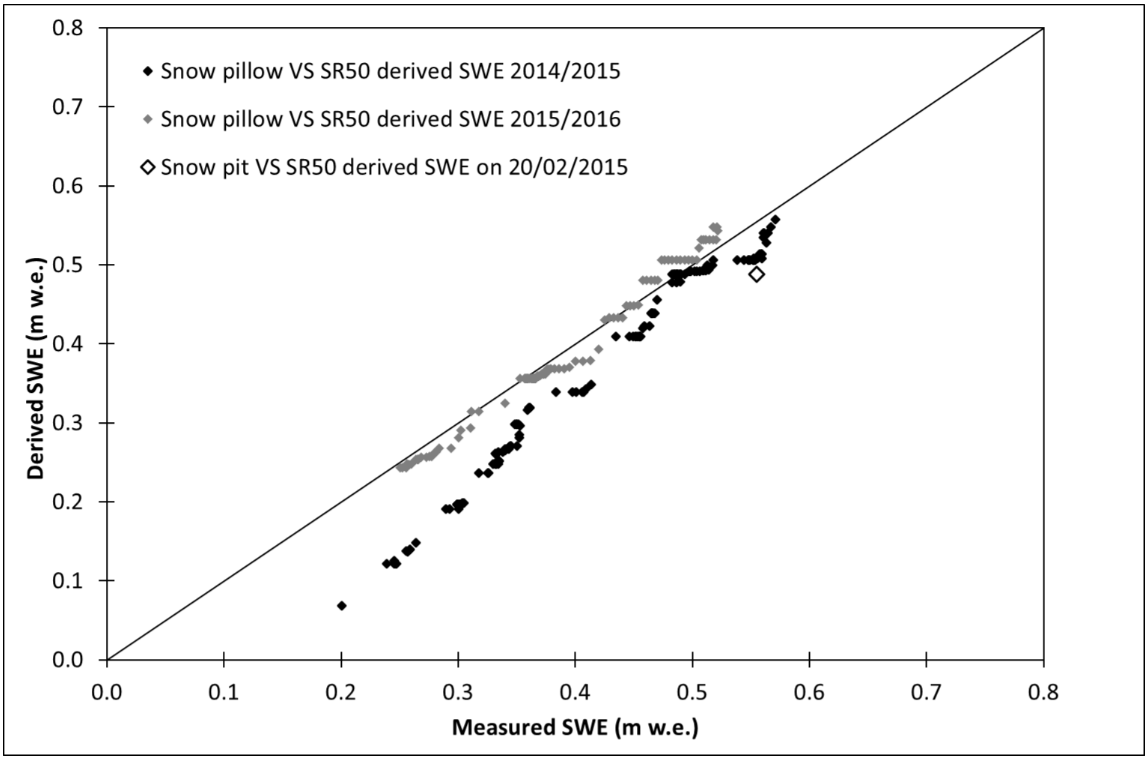

Figure 6: Scatter plots showing SWE measured by snow pillow and snow pit and derived applying Eq. (2) to data acquired by Campbell SR50. Two accumulation periods of measurements are shown from November 2014 to March 2015 and from February 2016 to May 2016. Every dot represents a daily value.

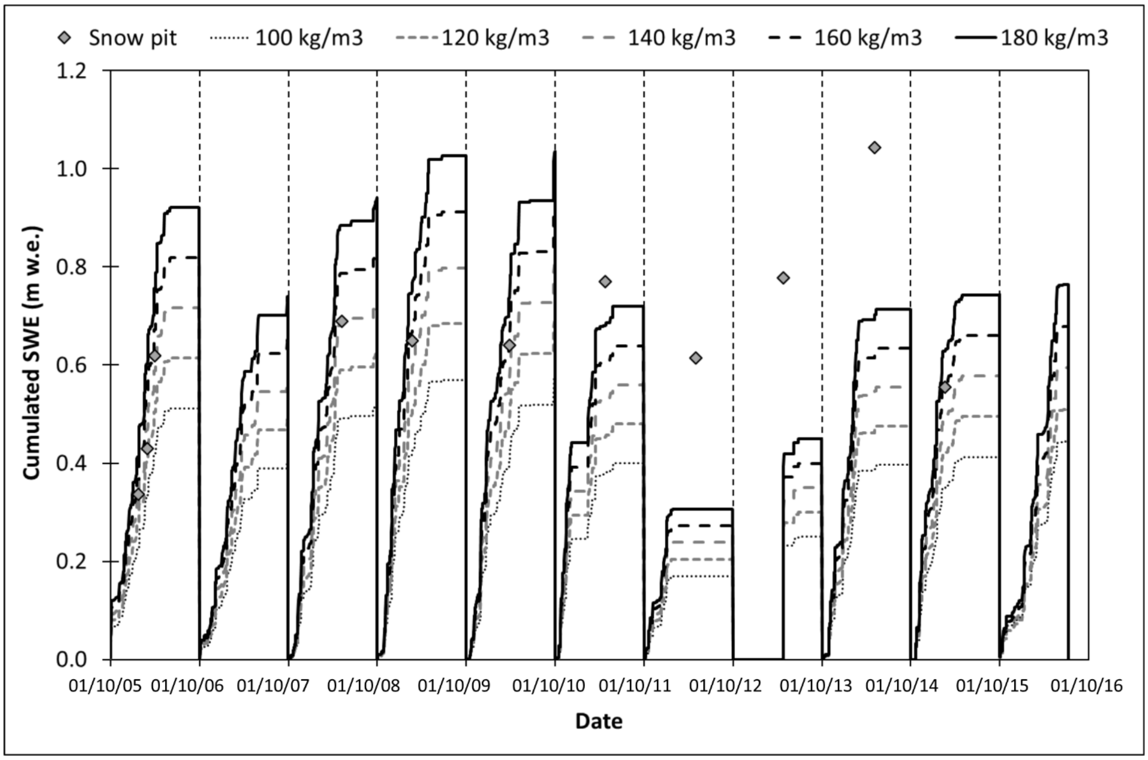

Figure 7: Comparison among *SWE* values derived from snow depth data acquired by SR50 sonic ranger (applying different values of fresh snow density) and *SWE* values measured by snow pits from 2005 to 2016. The dates shown are dd/mm/yy.