COST ES1404: Report of results from 2nd field campaign

28 February – 2 March 2017

Reykjavik, Iceland

Leena Leppänen, Nacho Lopez Moreno, Ladislav Holko, Steven Fassnacht, Pavla Dagsson-Waldhauserova, David Finger, Bartek Luks

Introduction

The 1st field campaign was held in Erzurum, Turkey, on 2-3 March 2016, where different methods to observe snow water equivalent (SWE) were demonstrated. The measurements of eight instruments were compared in shallow wet snowpack 10-34 cm deep at the first site. In addition, some of the instruments were compared also in 40-64 cm deep snow at the second site. The 1st field campaign documented large variations in density of snow (from 260 kg/m^3 to 431 kg/m^3 at the first site and 373 kg/m^3 to 447 kg/m^3 at the second site). In addition, suitability of the instruments to the wet snow conditions were noted.

The 2nd field campaign was held in Reykjavik, Iceland, on 28 February to 2 March 2017. It was focused on a more detailed comparison of SWE instruments in different snow conditions. In total, ten instruments were used for bulk SWE measurements. Additionally, several instruments were used for snow density profile measurements. The measurements were made at three different sites covering 37 – 159 cm depth range of rather dry snowpack.

A record snowfall in Reykjavik on February 25-26 2017

In the night from the 25 February to 26 February 2017, two days before the snow campaign, extremely intense snowfall was recorded in Reykjavík, the capital of Iceland (Figure 1). The snow depth increased from 3 cm at 18:00 on the Feb 25th to 51 cm at 9:00 on the Feb 26th, snowfall of 48 cm in total. The winds ranged between 2-7 ms^{-1}. The density of light powder snow measured at the Icelandic Meteorological Office was about 57.4 kgm^{-3} on February 26. The snow started to melt and the density was measured as 99-109 kgm^{-3} on February 27. The snow depth of 51 cm in Reykjavik was last time exceeded in January 1937 (55 cm) (reported by BBC, 27 February 2017). All roads were closed in the capital and surroundings, the cars were buried under snow and the only option for the campaign participants was to walk on the main streets.

Measurement sites

The three measurement sites were all located approximately 25 km south-east from Reykjavik in the foothills of the Hengill volcano. The first two sites were located in a lower open area close to the Hellisheiði geothermal power plant, and the third site was in the vicinity of the Bláfjöll ski resort (Figure 2). All sites were characterized by untouched natural snowpack. The measurements were conducted under the sunny clear sky conditions. The air temperatures were about -5.7 °C at Hellisheiði and -3.2 °C in Bláfjöll while the wind speeds were about 5.5 ms^{-1} at Hellisheiði and 2.4 ms^{-1} in Bláfjöll at the time of the measurements.

Site 1: North

The site 1 was located N 64.03866 W 21.40163 at elevation of 260 m a. s. l. north-west of the geothermal power plant Hellisheiði (Figure 2 a). The measurements took place approximately 200 m north from the power plant building and approximately 40 m from a small road. The snowpack was dry and snow depth was 53 cm. However, the snow surface was not smooth because it had some wind-driven variations. Under the hard surface layer was soft snow including some harder layers. The ground in the area is characterized by a lava plateau and covered by soft moss, which resulted varying height of snow values (Figure 2 b).

Site 2: South

The site 2 was located N 64.03665 W 21.40891 at elevation of 259 m a. s. l. approximately 190 m south from site 1 (Figure 2 a). The measurements took place in the parking yard of the power plant. The snowpack structure was similar to that observed in site 1, except height of snow was 48 cm. The main difference to site 1 was the ground, which was almost perfectly leveled and covered with grass and asphalt. However, snow depth had wind created variability (Figure 2 e).

Site 3: Ski area

The site 3 was located N 63.98342 W 21.65332 at elevation of 497 m a. s. l. in Bláfjöll (Figure 2 a). The site was located in the valley approximately 40 m from the road. The snowpack was dry and the mean snow depth was 123 cm.

Figure 1. Photos of the record snowfall in Reykjavik on 25-26 February 2017.

Figure 2. Location of the measurement sites in the SWE map ©Icelandic Meteorological Office in a), and three sites during the campaign and October 2017 in b) and d) site 1 (north), in c) and e) site 2 (south), and in f) and g) site 3 (Ski area).

Measurement methods

The bulk SWE measurements were made with ten snow tubes and the density profile measurements were made with cutting wedges (SnowMetrics and cylinder). Snow depth (HS) was also measured for each bulk SWE measurement. Generally, each bulk SWE measurement was made with a cylindrical tube, which was inserted in to the snowpack from surface, pulled out (with or without digging a pit) and weighed. The detailed instruments descriptions can be found in appendix A. On each site, approximately 20 m long snow pit (transect) was dug with smooth wall facing towards south. Basically, two to three places were measured with each instrument 1-6 times depending on measurement duration. Approximate location at transect was also noted. In addition, most of the measurements were made by both an expert and a novice user. As well, students of Reykjavik University measured SWE with U.S. Federal.

Twelve Reykjavik University MS student measured snow depth in pairs. At each location (Hellisheiði and Bláfjöll), the students measured snow depth at 11 points spaced at 1-m, called a measurement location. Each pair of students measured 8 to 11 locations, with each approximately 50-m apart.

Results and discussion

Overview of the collected data set is presented in Tables 1 and 2. The average values of all observations and average values of the instruments with relative standard deviations (RSD) and number of measurements for each site and measurement location are presented. RSD describes distribution of variation presented as percentage (ratio of the standard deviation to the mean), which is also called as coefficient of variation. The instruments are identified also by the country (i.e. country where the observer uses it normally).

Based on the Table 1, when considering all observations for the all sites, RSD for HS varied between 11.5 % and 48.3 %, for the snow density between 9.5 % and 16.1 %, and for SWE between 13.1 % and 18.8 %. Average RSD was smallest for sites 1 and 2 (11.5 %). Totally, 148 measurements were made, 54 at site 1, 72 at site 2 and 12 (21 with U.S. Federal) at site 3. Based on the Tables 2-4, RSDs for different instruments were between 0.5 % and 15 %, 0 % and 14 %, 0 % and 15 % for SWE, HS and snow density respectively. Average of all SWE RSDs for all sites and instruments were 8 %.

Inter-comparison of the instruments was not possible based on the collected data set, because the absolute SWE value is not known and natural variability of snow properties are high. Therefore, individual instruments are evaluated by RSDs and average SWE compared to the site average of all instruments. To explain those, we use snow depth and density measurements as well as other available information as properties of the ground below. However, RSD is highly dependent on the number of observations, and therefore instruments with more observations has usually higher RSD. In addition, some of the measurements had only 1-2 repetitions when RSD is not giving trustable estimation of the repeatability. Total RSD calculated over all measurements at the site includes spatial variability of snowpack. Therefore RSDs are not directly comparable and gives weak estimation of the measurements accuracy.

Site variability

Site 2 was the only where all instruments were used, and it had also smallest RSD in HS (Table 1). Most of measured SWE values were between 120 and 140 mm, both Italian samplers gave larger values, and U.S. Federal and SnowHydro gave smaller values, on average on site 2. For SWE, RDS was below 10 % for Lithuanian VS-43, Korhonen-Melander sampler, IG PAS, Dolfi, SnowHydro and Italian samplers. For Estonian VS-43 RSD was little bit over 10 %, and U.S. Federal below 15 %. ETH had only one observation per location, and RSD could not be calculated. However, custom EV2 and EV2 had only two observations, which is not enough for strong conclusions. EV2 had RSD of 20 % at site 3, which originated from density variations while HS was the same for all three measurements.

For site 1 the SWE values were between 111 and 133 mm. Estonian VS-43 , Lithuanian VS-43 and SnowHydro had values below 120 mm, and ETH, IG PAS and Dolfi had values 120-130 mm, while Korhonen-Melander sampler had over 130 mm. RSDs were below 10 % only for SnowHydro, Estonian VS-43 and IG PAS. RSD below 15 % were for Korhonen-Melander sampler, Lithuanian VS-43, and Dolfi. Again ETH had not enough measurements to calculate the RSD.

Scatterplots of snow depth and density measurements for all sites are presented in Figure 3. Site 3 had the largest variability in both density and snow depth. Site 2 had smaller variability of snow depth than Site 1, originating from type of the ground surface. Site 2 had larger variability in density than site 1. However, the most variable density values in site 2 came from the instruments which were not used in site 1. The site 3 had the deepest snowpack and highest variations in snow depth. Density variability of the site was close to site 2. All sites had natural variability created by wind. There is a weak correlation between snow density and depth at all sites. Therefore, it is more straightforward to compare derived density values than SWE observations.

Box plots of snow density and depth observations are shown in Figure 4 in the same order as measurement locations in transects. Sites 1 and 3 had no clear trends either for density or snow depth along transect. Site 2 had clearly larger snow depth values in the middle of transect, however there was not the same trend in the density. SnowHydro had clear trend at site 2 so that snow depth values close to each other had similar density values meaning that different locations had different snow properties, which caused the large average RSD in Tables 2-4. Other instruments had no similar trends for site 1 or site 2.

Table 1. Minimum, maximum and average values as well as relative standard deviation (RSD) for snow depth (HS), density and SWE measured by all instruments used in the trenches. Total number of measurements (N) for each site is shown. Measurement of U.S. Federal at site 3 are excluded because they were not made at the same transect.

	Site 1			**Site 2**			**Site 3**		
	HS (cm)	**Density (kg/m³)**	**SWE (mm)**	**HS (cm)**	**Density (kg/m³)**	**SWE (mm)**	**HS (cm)**	**Density (kg/m³)**	**SWE (mm)**
Min	37.0	188.7	88.8	40.0	159.0	88.9	97.0	241.1	318.3
Max	67.0	268.4	170.0	56.0	392.9	176.8	159.0	419.8	569.3
Ave	52.6	230.6	121.1	48.3	261.0	126.5	122.8	354.5	433.8
RSD (%)	11.4	9.5	13.2	8.11	13.2	13.1	12.4	16.1	18.8
Ave RSD (%)	11.4			11.5			15.8		
N	54			72			12		

Table 2. Average SWE (mm) with relative standard deviation (RSD) and number of measurements (N) obtained from bulk SWE measurements for all instruments and all sites (grey) and separately for each measurement location. Average total RSDs and total number of measurements at all sites is also shown.

Instrument	Country	Site 1 (North)			Site 2 (South)			Site 3 (Ski area)			Total	
		Average	RSD	N	Average	RSD	N	Average	RSD	N	RSD	N
VS-43	Estonia	111.1	5.9	9	126.7	10.1	5	-	-	0	8.0	14
	1	116.9	2.8	4	126.7	10.1	5					
	2	106.4	4.2	5								
VS-43	Lithuania	114.3	12.6	10	129.8	5.0	10	341.4	0.5	2	6.0	22
	1	123.9	3.7	5	135.4	2.9	5	341.4	0.5	2		
	2	104.6	13.8	5	124.2	2.2	5					
ETH	Switzerland	128.3	5.7	3	134.6	6.6	3	569.3	-	1	4.1	7
	1	127	0	1	48.0	0	1	569.3	-	1		
	2	120	0	1	146.0	0	1					
	3	138	0	1	134.0	0	1					
K-M sampler	Finland	131.7	11.0	9	129.8	5.8	6	-	-	0	8.4	15
	1	125.2	5.2	4	125.5	1.1	2					
	2	137	12.3	5	132.0	6.3	4					
IG PAS	Poland	125.5	4.8	3	123.5	4.8	7	-	-	0	4.8	10
	1	125.5	4.8	3	129.7	0	3					
	2				124.7	0	1					
	3				116.9	0	3					
Dolfi	Slovakia	126.8	15.8	11	131.7	4.9	10	495.0	3.1	4	7.9	25
	1	113.8	13.3	6	135.6	2.9	5	519.2	0	1		
	2	142.4	9.1	5	127.8	5.1	5	487	1.6	3		
SnowHydro	Spain	117.1	11.6	9	113.5	15.4	14	431.3	3.7	2	10.2	23
	1	121.0	5.0	3	102	0	3	431.3	3.7	2		
	2	128.0	8.8	3	130.5	1.1	6					
	3	102.5	6.9	3	91.0	1.5	3					
Custom EV2	Italy	-	-	0	143.8	6.1	3	-	-	0	5.8	4
	1				145.0	7.3	2					
	2				141.4	0	1					
EV2	Italy	-	-	0	168.8	6.7	3	371.1	19.8	3	9.9	5
	1				176.8	0	2	371.1	19.8	3		
	2				152.8	0	1					
U.S. Federal	USA	-	-	0	116.2	12.7	13	186.2	14.0	9	13.3	22
	1				121.9	14.1	5	186.2	14.0	9		
	2				105.8	14.9	3					
	3				116.9	4.3	5					

Table 3. Average HS (cm) with relative standard deviation (RSD) and number of measurements (N) obtained from bulk SWE measurements for all instruments and all sites (grey) and separately for each measurement location. Average total RSDs and total number of measurements at all sites is also shown.

Instrument	Country	Site 1 (North)			Site 2 (South)			Site 3 (Ski area)			Total	
HS		**Average**	**RSD**	**N**	**Average**	**RSD**	**N**	**Average**	**RSD**	**N**	**RSD**	**N**
VS-43	Estonia	53.4	9.2	9	51.0	2.7	5	-	-	0	5.9	14
	1	58.0	5.0	4	51.0	2.7	5					
	2	49.8	5.2	5								
VS-43	Lithuania	47.4	11.6	10	48.1	4.1	10	99.0	2.0	2	5.9	22
	1	50.8	1.4	5	49.75	0.8	5	99.0	2.0	2		
	2	44.0	13.9	5	46.4	2.9	5					
ETH	Switzerland	50.6	5.6	3	49.3	8.4	3	159.0	0	1	4.7	7
	1	51.0	0	1	48	0	1	159.0	0	1		
	2	47.0	0	1	55	0	1					
	3	54.0	0	1	45	0	1					
K-M sampler	Finland	56.1	9.2	9	48.5	7.0	6	-	-	0	8.1	15
	1	580.	1.2	4	44	2.2	2					
	2	54.6	12.0	5	50.75	2.5	4					
IG PAS	Poland	50.0	0	3	46.7	1.4	7	-	-	0	0.7	10
	1	50.0	0	3	47	0	3					
	2				48	0	1					
	3				46	0	3					
Dolfi	Slovakia	51.8	11.3	11	47.1	2.4	10	120.5	3.4	4	5.7	25
	1	49	11.9	6	47	1.3	5	126	0	1		
	2	55.2	6.9	5	47.2	3.1	5	119	2.6	3		
SnowHydro	Spain	56.7	8.4	9	48.5	13.1	14	119.5	0.4	2	7.3	23
	1	57.0	2.4	3	48.3	0.9	3	119.5	0.4	2		
	2	61	8.0	3	55.1	1.2	6					
	3	52.3	4.7	3	40.8	2.4	3					
Custom EV2	Italy	-	-	0	50	3.2	3	-	-	0	4.3	4
	1				49.0	2.0	2					
	2				52	0	1					
EV2	Italy	-	-	0	49.6	7.4	3	132.0	0	3	2.6	5
	1				47.5	5.2	2	132.0	0	3		
	2				54	0	1					
U.S. Federal	USA	-	-	0	48.3	9.0	13	56.7	16.0	9	12.5	22
	1				45.0	2.1	5	56.7	16.0	9		
	2				55.8	0	3					
	3				47.6	1.3	5					

Table 4. Average density (kg/m^3) with relative standard deviation (RSD) and number of measurements (N) obtained from bulk SWE measurements for all instruments and all sites (grey) and separately for each measurement location. Average total RSDs and total number of measurements at all sites is also shown.

Instrument	**Country**	**Site 1 (North)**			**Site 2 (South)**			**Site 3 (Ski area)**			**Total**	
Density		**Average**	**RSD**	**N**	**Average**	**RSD**	**N**	**Average**	**RSD**	**N**	**RSD**	**N**
VS-43	Estonia	208.8	6.9	9	248.0	7.8	5	-	-	0	7.3	14
	1	202.5	8.0	4	248.0	7.8	5					
	2	214	4.7	5								
VS-43	Lithuania	241.0	3.4	10	270.0	2.8	10	345.0	1.4	2	2.5	22
	1	244	3.2	5	272.0	2.7	5	345.0	1.4	2		
	2	238	3.1	5	268	2.7	5					
ETH	Switzerland	253.3	1.2	3	273.8	6.2	3	358.1	0	1	2.4	7
	1	249.0	0	1	258.3	0	1	358.1	0	1		
	2	255.3	0	1	265.5	0	1					
	3	255.6	0	1	297.8	0	1					
K-M sampler	Finland	235.4	8.3	9	268.5	6.7	6	-	-	0	7.5	15
	1	215.8	4.1	4	285.4	3.4	2					
	2	251.0	3.6	5	260.0	5.8	4					
IG PAS	Poland	251.1	4.8	3	264.3	3.8	7	-	-	0	4.3	10
	1	125.5	4.8	3	276	0	3					
	2				260	0	1					
	3				254.1	0	3					
Dolfi	Slovakia	243.7	6.5	11	279.5	3.7	10	410.8	1.4	4	3.8	25
	1	232.1	3.5	6	288.4	1.7	5	412	0	1		
	2	257.7	4.1	5	270.5	2.1	5	411	1.6	3		
SnowHydro	Spain	205.9	5.0	9	227.0	4.9	14	361.0	3.3	2	4.4	23
	1	212.1	3.4	3	211.0	0.9	3	361.0	3.3	2		
	2	209.9	4.4	3	235.0	2.2	6					
	3	195.7	2.7	3	223.8	0.7	3					
Custom EV2	Italy	-	-	0	288.3	8.8	3	-	-	0	7.7	4
	1				296.4	9.3	2					
	2				272.0	0	1					
EV2	Italy	-	-	0	343.2	13.2	3	280.4	19.8	3	12.5	5
	1				373.3	5.2	2	280.4	19.8	3		
	2				283.0	0	1					
U.S. Federal	USA	-	-	0	243.1	17.2	13	332.0	13.5	9	15.3	22
	1				273	13.7	5	332.0	13.5	9		
	2				189.3	14.9	3					
	3				245.9	3.6	5					

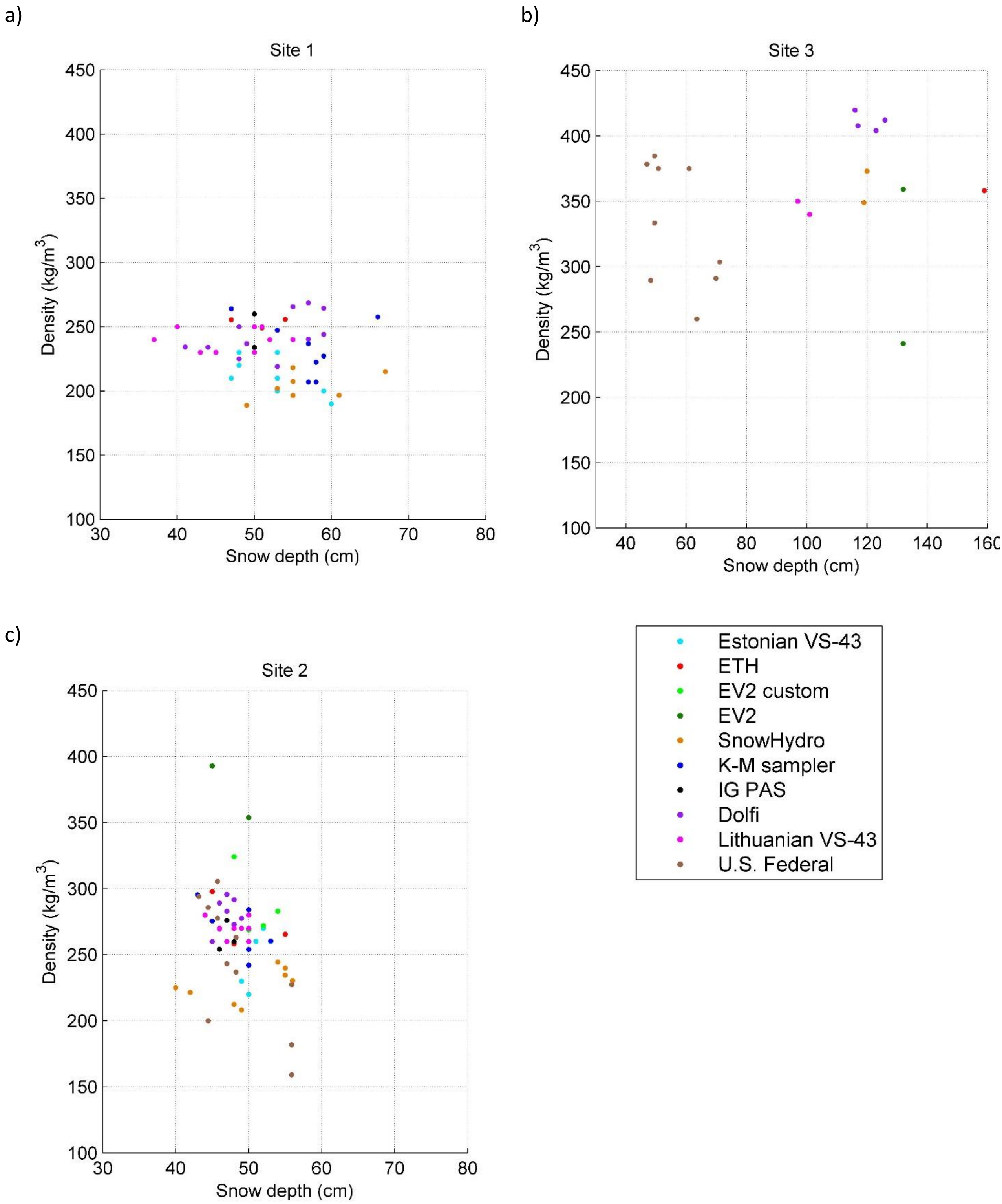

Figure 3. Density of bulk SWE tubes are plotted towards snow depth for all sites: a) site1, b) site 3 and c) site2.

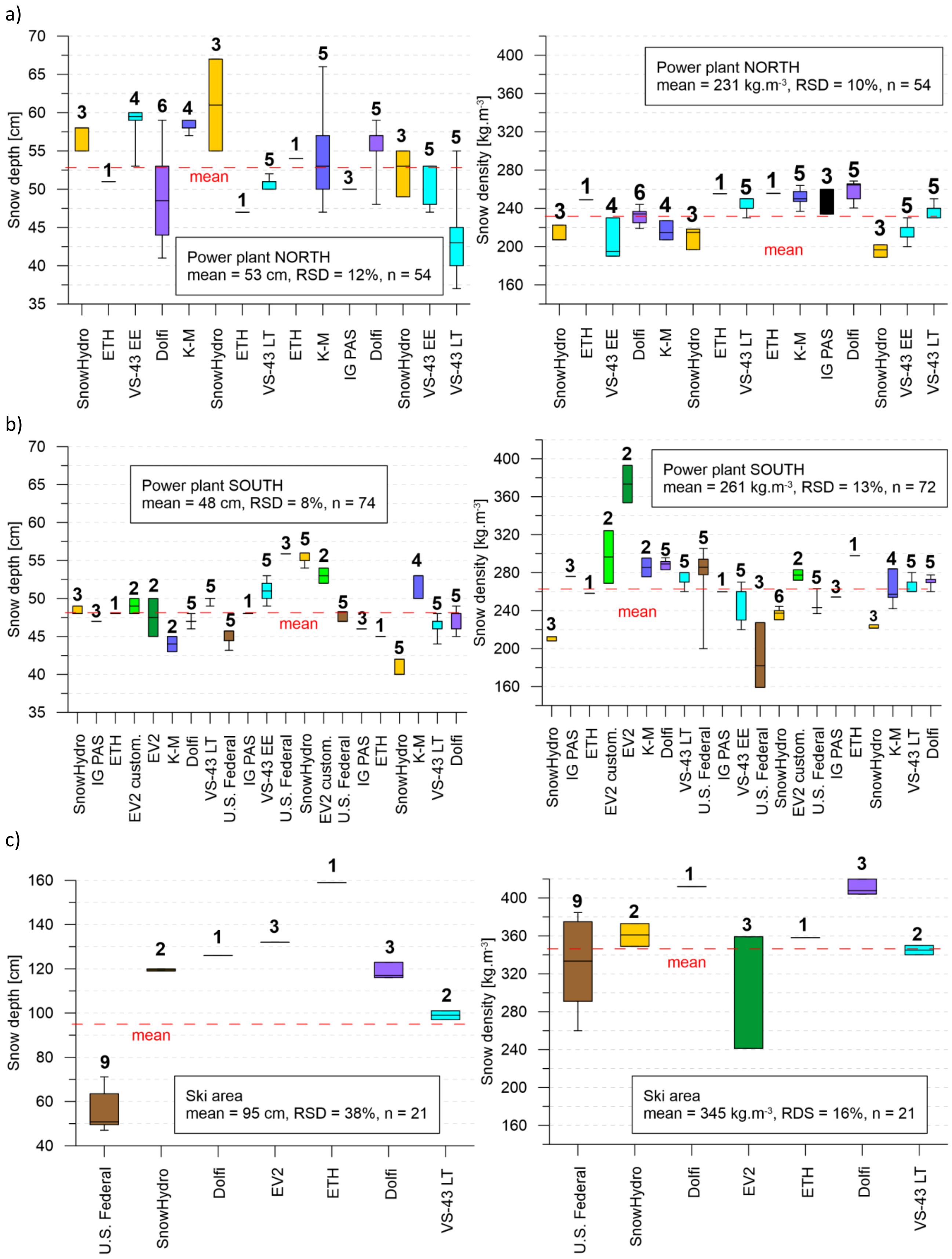

Figure 4. Average of snow depth and density from bulk SWE tubes for a) site 1, b) site 2 and c) site 3. Number of measurements is shown above each boxplot. Maximum and minimum values are marked with whiskers.

Variability from individual instruments

Estonian VS-43 had total 14 measurements with average SWE close to site average at site 2 and smaller at site 1, with RSD 3-10 %. Site 1 variability originates from HS difference between the locations, while the density values were closer to each other (Figure 4). Average density was 10-20 kg/m^3 smaller than the average of all instruments for sites 1 and 2. Lithuanian VS-43 had total 22 measurements from all three sites. Average SWE was 7 mm smaller for site 1, 3 mm larger for site 2 and 17 mm larger for site 3 compared to average from all instruments. RSDs were 0.5-14 %, so that largest value was for site 1 where HS measurements at one location had much variability, but the density values were closer to each other. The instrument had 10 kg/m^3 larger density values than the average for sites 1 and 2, and 10 kg/m^3 smaller for site 3. The difference between the averages of VS-43 SWE measurements was 3 mm for sites 1 and 2, however there was some difference in both HS and density so that Estonian instrument had larger HS but smaller density than Lithuanian.

ETH had total 7 measurements with average SWE larger at all sites than the average of all instruments. Sites 1 and 2 had less than 10 mm difference to site average SWE. Site 3 had only one ETH measurement which had 65 cm larger snow depth than the site average in Table 1. ETH had 10-20 kg/m^3 larger average density values for sites 1 and 2, while site 3 observation was only 4 kg/m^3 larger. Korhonen-Melander sampler had total 15 measurements from sites 1 and 2 so that total SWE was maximum 10 mm larger than the site average. RSDs were 5-12 % and 1-6 % respectively. Site 1 had large variations in snow depth at the location, where the ground had large stones. The instrument had 5-10 kg/m^3 larger average density values for sites 1 and 2 than the average of all instruments. IG PAS had total 10 measurements from sites 1 and 2 with SWE values close to the site averages of all instruments. RSDs were 5 and 0 % respectively. It had 20 kg/m^3 larger average density value for site 1 and only 4 kg/m^3 larger value for site 2.

Dolfi had total 25 measurements with SWE values 7 mm larger than site averages, except for site 3 where difference were approximately 170 mm. Densities at site 3 were larger than with the other instruments. RSDs for sites 2 and 3 were below 5 % and for site 1 RSD were 13 %, where it was caused by variability in snow depth. Dolfi had 10-20 kg/m^3 larger values than average density of all instruments for sites 1 and 2, and 50 kg/m^3 larger for site 3. SnowHydro had total 23 measurements. Site 1 had 4 mm smaller value, site 2 had 13 mm smaller value and site 3 had 4 mm larger value than site averages. Site 2 had lower density values than most of the other instruments, which explains the low SWE value. RSDs were 5-9 % for site 1, below 2 % for site 2 and 4 % for site 3. Site 2 had difference in snow depth between the locations, which is the reason of larger average RSD (15.4 %). SnowHydro had 25-35 kg/m^3 smaller density values compared to site average for sites 1 and 2, and 7 kg/m^3 larger value for site 3.

Custom EV2 had total 3 measurements from site 2, and EV2 total 6 measurements from sites 2 and 3. Average SWE values were 20-50 mm larger than the site averages. RSDs were 0-20 %, based on two measurements at both sites. RSD of EV2 at site 3 originates from density variability. Custom EV2 had 25 kg/m^3 larger density value than the average for site 2. EV2 had 70 kg/m^3 larger average value for site 2 and 70 kg/m^3 smaller average value for site 3. U.S. Federal had total 22 measurements from sites 2 and 3. However, measurements at site 3 were not made from the same transect. Therefore, the results are not directly comparable with others. Both average SWE values were smaller than the site averages, especially site 3 had 140 mm smaller value than the site average. Snow depth values at site 3 were lower than for other instruments. Lower SWE for site 2 originates from the lower density values, which were mainly measured by the novice observer. RSDs were 1-14 %, which originates at site 2 from variability in density and at site 3 variability of both snow depth and density. U.S. Federal had 10 kg/m^3 larger average density value for site 2 than the average of all instruments and 20 kg/m^3 smaller average density for site 3.

Spatial variability of snow depth outside the transects

Variability of the snow depth data set collected by the students is presented in the Figures 5 and 6. The students collected data over a much larger area so greater net variability is expected (HS from 10 to 140 cm). Variability at each plot (10-m transect) was from 6.4 to 102% (Figure 5), averaging 30.4 % at Hellisheiði and 33 % at Bláfjöll.

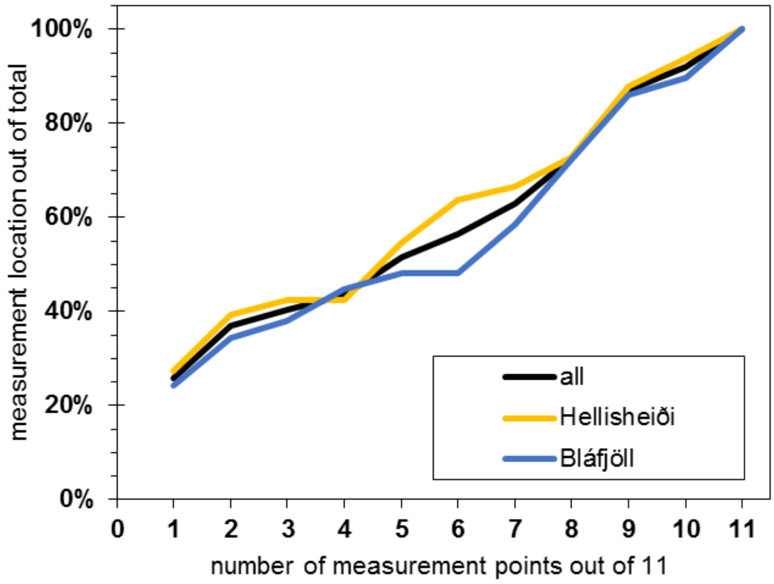

Figure 5. Snow depth variability based on the Reykjavik University student measurements (33 locations at Hellisheiði and 29 locations at Bláfjöll). A 5% error from the mean is used.

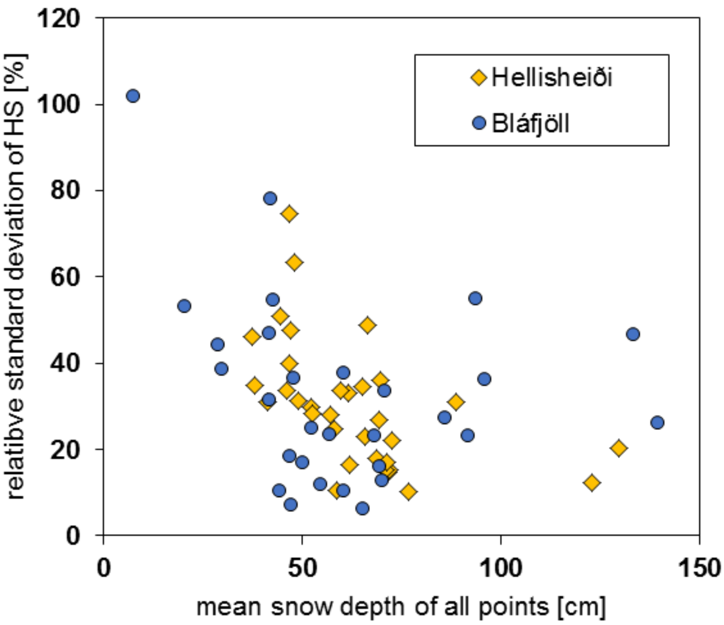

Figure 6. Relative standard deviation of the Reykjavik University student measurements (33 locations at Hellisheiði and 29 locations at Bláfjöll).

Sources of variability

Comparison between measurements of expert and novice did not show significant differences, because there were too small amount of measurements from both expert and novice to make strong conclusions. Therefore, the observer's experience related variability cannot be included in the conclusions. Data from the measurements made by the novices are used in the analysis, and therefore observer related differences exists.

Measurement accuracy depends on the instrument, observer and environment. Snowpack has natural variability originating from type of ground surface, elevation changes and wind. It is therefore difficult to separate the effect of the variability induced by an observer or instrument from the natural variability.

The sources of variability evaluated by observers were snow sticking to tube, heavy snow, ground surface (moss and rocks), hard layers in snowpack, icy snow on the bottom at site 3, thin snowpack at sites 1 and 2, and high snowpack at site 3. The sources varied between the instruments as those are developed for different environments.

Summary

Snow depth varied between 37-67 cm at site 1, 40-56 cm at site 2 and 97-159 cm at site 3. Density varied between 189-268 kg/m^3 at site 1, 159-392 kg/m^3 at site 2 and 241-420 kg/m^3 at site 3. Generally, Estonian VS-43, Lithuanian VS-43, ETH, K-M sampler, IG PAS, Custom EV2 and U.S. Federal gave maximum 10 % difference in density to the site averages for all sites where measurements existed. SnowHydro gave 13 % smaller values than the site averages for site 2, and value with maximum 10 % difference for sites 1 and 3. Dolfi gave 16 % larger value for site 3 and value with maximum 10 % difference for site 2. EV2 gave 31 % smaller value for site 2 and 21 % larger value for site 3. However, spatial variability of snow depth and density were large at the sites.

The field campaign showed that in the case of SWE, which is typically the main snow characteristic in operational hydrology, the mean values obtained for the snow course (transect) with different instruments can differ by less than 10 % if the suitable amount of measurements (i.e. at least 3) is done. Natural spatial variability of SWE is difficult to separate from variability originating from observer and instrument.

APPENDIX A: Description of used snow tubes

COST ES1404

2nd field campaign in Iceland

1 March 2017

1. Estonian VS-43
2. Lithuanian VS-43
3. ETH cylinder
4. Korhonen-Melander sampler
5. IG PAS snow tube
6. Dolfi
7. SnowHydro
8. Custom EV2
9. EV2
10. U.S. Federal Sampler

1) VS-43 Estonia

Name of the observer: Kairi Vint

Instrument dimensions: instrument height: 60 cm; cross sectional area 50 cm^2.

Reference: no reference, but scale is calibrated correctly

Instrument description

SWE tube VS-43 consists following elements as described in Figure. SWE tube VS-43 in weighing position is shown in Figure 1.

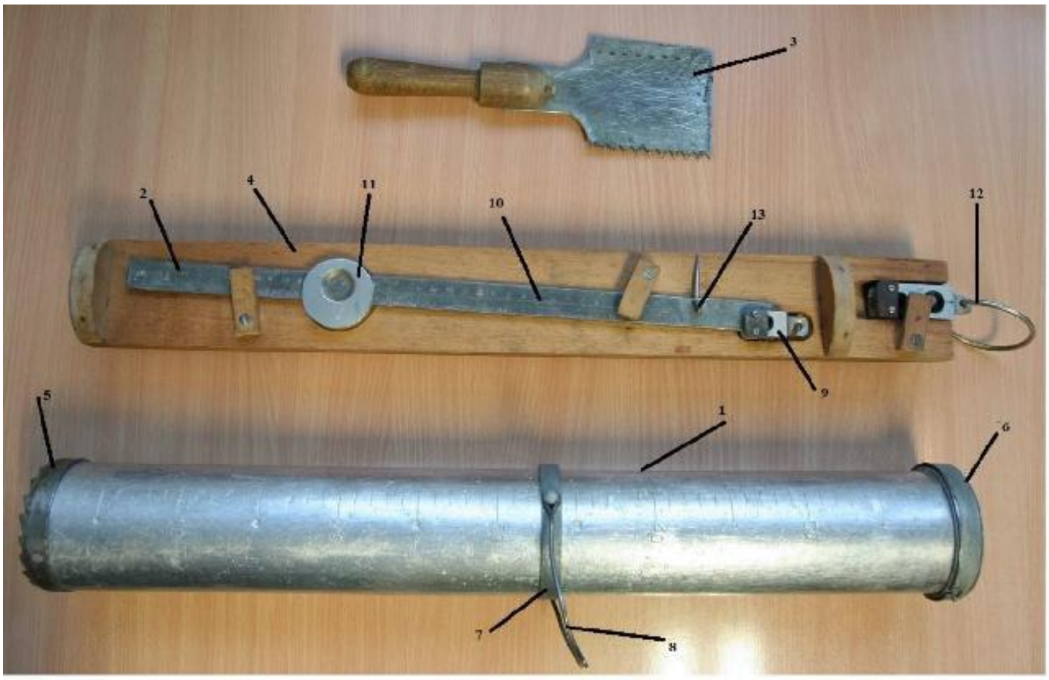

Figure A1. SWE tube VS-43. 1 – cylinder; 2 – scale; 3 – a sharp shovel; 4 – wooden base; 5 – a sharp ring; 6 – cover of cylinder; 7 – hoop; 8 – handle; 9 – hook of scale; 10 – scale bar; 11 –heft; 12 – handle.

Description of default snow conditions for instrument usage

It is not known default conditions for instrument usage. In Estonia we start measurements only when snow depth is at least 5 cm and more.

Possible error sources in default conditions:

Strong winds and/or human error (for example: especially in extremely cold weather conditions).

Possible error sources during the field campaign in Iceland:

Main reasons for errors are that Estonian observers hand began to ache in Iceland (snow was heavy and weighing very time-consuming), defiantly also this caused extra loss of time that observer was not the expert, but only novice and practice has been in Estonia only with much lighter snow.

General comments of the instrument usage during the field campaign in Iceland

Snow discharge from the tube were more time-consuming than expected and it caused terrible loss of time and Estonian observer measured much less than other observers. Maybe any auxiliary tool would have been helpful for cleaning and removing heavy snow from the tube. Definitely, Estonian observer right hand ache in Iceland was an obstacle to get sufficient amount of measurements.

2) VS-43 Lithuania

Name of the observer(s): Justinas Kilpys

Instrument dimensions: height – 60 cm, sampling area – 50 cm^2, accuracy of weighting scale – 5 g.

Reference: detail description is available only in printed version (in Russian language). Short description (in Russian): http://zapadpribor.com/vs-43-snegomer/

Instrument description

Short snow bulk measurement tube VS-43 is made by Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). The snow column measuring tube is made from aluminum and has a metal cuter at the end. Its height is 60 cm, the sampling area is 50 cm^2 (diameter = 8 cm). The weighting scale is mechanical and its accuracy is 5 g. Maximum weight of sample is 1.5 kg. To weight the sample you have to put the blade under the cutter and turn the tube upside down. The tube has a cap on top, so snow sample does not fall out.

Figure A2. SWE tube VS-43 with the scale and the blade.

Description of default snow conditions for instrument usage

It is created for operational use in the snow courses. It is best for the shallow snow (up to 60 cm), but can be used for deeper snow as well (when bulk measurements should be done in layers). It is not recommended to use it, if weight of snow sample is less than 50 g. The air temperature of working environment can be from -70°C to +45 °C. If it was kept inside the warm place, it should be kept outside for 10 minutes, to reach the same temperature as environment.

Possible error sources in default conditions

The weighting scale has accuracy of ± 5 g. The accuracy of snow depth measurements ± 1 cm.

Possible error sources during the field campaign in Iceland

The snow in all locations was sticking to the metal tube and it was difficult to clean it between measurements. This could lead to the errors in weighting (although, before each measurement I made the calibration weighting of empty tube).

General comments of the instrument usage during the field campaign in Iceland

It was very difficult to use the short tube in the deep snow (ski area) – I needed to take the bulk sample in two peaces and was using hammer to cut through the ice crust. Also, in all location snow was sticking to the metal tube, and I always needed to do the calibration weighting (checking the “0” values of the empty tube) - it was very time consuming activity.

3) ETH cylinder Switzerland

Name of the observer(s): Julien Anet, Christoph Marty

Instrument dimensions: 55 cm length, 9.5 cm diameter

Instrument description

Metallic cylinder with a sharpened rim on one side, which mass can be directly measured with a specific scale in mm water equivalent.

Figure A3. Left: inserting cylinder to snow. Right: weighing of the sample.

Possible error sources during the field campaign in Iceland

Thick ice layers can be a problem

General comments of the instrument usage during the field campaign in Iceland

Worked well. In the ski area thanks to the rubber hammer.

4) Korhonen-Melander sampler Finland

Name of the observer(s): Leena Leppänen and Ali Nadir Arslan, Finnish Meteorological Institute

Instrument dimensions: 70 cm high and 10 cm in diameter

Reference: L. Leppänen, A. Kontu, H-R. Hannula, H. Sjöblom, J. Pulliainen, Sodankylä snow survey program, Geosci. Instrum. Method. Data Syst., 5, 163-179, doi:10.5194/gi-5-163-2016, 2016.

Instrument description

FMI sampler is made of black plastic tubing. There is a removable lid with a handle on one end of the tube, and the other end is re-enforced with a sharpened metal ring. Each tube is paired with a scale and the pair is calibrated to show SWE directly. A centimeter scale on the outside of the tube allows for the measurement of HS for density calculation. Tubes with different length and diameter are used in Finland, Finnish Environmental Institute uses shorter tube made of metal. Tubes were manufactured by FMI and small company in Finland.

Figure A4. Left and middle: tube used in Sodankylä (removal from the snowpack and weighing). Right: tube used by Finnish Environmental Institute.

Description of default snow conditions for instrument usage

Below described conditions are typical for snowpack in Sodankylä, Finland. Snow starts to accumulate in end of October or beginning of November. Maximum snow depth around 80-100 cm exists in March. Snow is totally melted in mid-May. Snowpack is dry at most of the winter, and beginning of April it starts to melt.

Simplified snowpack consists usually following layers: above ground is soft depth hoar layer with large grains, above that is little bit harder layer of rounded grains, and at top is soft and light layer of new snow. There are several thin (0.5-1 cm) crust layers in snowpack.

Possible error sources in default conditions

Vegetation in snow, additional snow stuck to outside of the tube, loose grains get easily out when lifting the tube up, if shovel is not properly under the tube, wind makes scaling difficult. For deeper snowpack than 60 cm, measurement needs to be made two times to cover whole HS, while recording actual depth of the measurements is more difficult. Accuracy of reading HS is 1 cm and SWE 1 mm.

Possible error sources during the field campaign in Iceland

In north pit uneven ground surface caused difficulties for using the instrument, and some cases snowpack was not possible to sample from whole depth (especially when snow was beneath rocks). Also shovel was difficult to use for lifting the tube up, therefore it was not used in every measurement. However, snow was so dense that it stayed very well inside the tube also without the shovel. Sites had also soft moss in some locations when sampler sink to the vegetation, and noted HS had error (too large HS). Snowpack was also too hard for the sampler, and force was needed to push it until ground. That may cause error in instrument vertical direction, and possibly all snow has not stayed inside the tube. Snow was also little bit wet (grains stuck together) which caused snow catching to the tube. Tube was weighted before measurements, but during the measurement outside of the tube might have extra snow.

General comments of the instrument usage during the field campaign in Iceland

The tube was more difficult to use in Iceland than in normal conditions in Sodankylä. Snow was too hard and it stuck to the instrument. Cleaning of the instrument took lot of time compared to usual in Sodankylä. However, sampling was possible to make successfully.

Other comments

The tube has sharpened cutting edge, which is not sharp enough for hard snowpack as experienced in Turkey or Iceland.

5) IG PAS snow tube (prototype) Poland

Name of the observer(s): Bartłomiej Luks

Instrument dimensions: tube inner diameter: 7 cm, tube working length: 50 cm tube length with cap: 58 cm, tube sampling volume: 1924 cm^3

Instrument description

Stainless steel tube cutter with polyethylene cap and collapsible handle. Snow sample can be weighted directly in tube. Designed for coastal tundra snow monitoring programme in Polish Polar Station Hornsund, Svalbard. It has reinforced sharpened edge for cutting through dense snow and icy layers. Tube has depth ticks marked on one side (1 cm resolution). Detachable PE cap can be secured on top side, which lets weighting of the sample directly in the tube. After hitting the ground or 50 cm layer, bottom of the sampler has to be secured with shovel or plate and turned upside down for weighing. Instrument weights approximately 1650 g, although it should be weighted during sampling campaign as there might be some snow/ice left on sides of the sampler. For COST field campaign it was used with PESOLA MacroLine 5kg spring scale. It can be used with any electronic/mechanical hand scale.

Figure A5. IF PAS

Description of default snow conditions for instrument usage

Can be used with most types of snow. Works best in dense snow. Suitable for sampling very hard layers and ice formations.

Possible error sources in default conditions

Needs special attention in wet/sticky snow, as snow might stick to inside surface of the tube.

Possible error sources during the field campaign in Iceland

Didn’t noticed any error sources during field campaign

General comments of the instrument usage during the field campaign in Iceland

Generally it worked well for a prototype.

6) Dolfi (**D**reamingly **O**riginal **L**ight **Fi**berglass) Slovakia

Name of the observer(s): Ladislav Holko

Instrument dimensions: length 1 m, diameter 8 cm (area 50 cm^2).

Instrument description

The snow tube is made in the Czech Republic. The first version was made at Czech Hydrometeorological Institute already in 1988. Currently, version 6 with the double rustles cutter is produced by the same person (already retired). The snow tube is made of glass fiber and has the metallic cutter. Different length of the tube can be made by the producer according to the requests of the users. Snow depth can be measured by using the scale laminated on the wall of the tube (with resolution of either 5 cm or 1 cm). Snow tube version 5 which was used in Iceland has the steel, zinc-coated cutter. After insertion of the tube to the snow, the snow collected in the tube can be pressed by a plunger to ensure that all snow core is taken out without the necessity of digging the snow pit. Because of larger diameter of the tube, it is mostly possible to check visually if all snow was collected (the soil surface is visible at the bottom of the hole made by the tube). Owing to the material, the snow does not stick on the walls of the tube and emptying of the tube is easy as well. Electronic scale used with the tube was calibrated to provide the readings in millimeters of SWE. Its measuring range was 0.05 kg (10 mm) to 7 kg (1400 mm), the weighting accuracy guaranteed by the producer was 7 g (1.4 mm of SWE).

a)

b)

Figure A6. Dolfi, a) metallic cutter and b) weighing of the sample.

Description of default snow conditions for instrument usage

The tube was used to sample snow at various conditions from fresh to icy snowpack including snow layers of varying density.

Possible error sources in default conditions

Sometimes it happens that the tube does not collect a few centimeters of snow at the soil surface.

Possible error sources during the field campaign in Iceland

A few centimeters of very icy snow near the soil bottom (2-4 cm) were not collected by the tube at Blafjöll. Consequently, the snow depth was reduced by those 2-4 centimeters which effectively means that it is supposed that the density of that thin layer of snow is the same as that sampled by the tube above it.

General comments of the instrument usage during the field campaign in Iceland

I did not experience any problems during measurements at the geothermal power plant. The entire depth of the snowpack was sampled quickly which allowed to make 5 measurements at each side of the two trenches.

Measurement was possible even the very icy snow layer at Blafjöll. However, because the snowpack was higher than the length of the snow tube and the lower layer was very hard, it was necessary to dig partially (first sample contained the new snow layer with smaller density and then the icy layer was sampled in two samples). As a result of it the measurement took longer and only 4 measurements were done.

7) SNOWHYDRO Spain

Name of the observer(s): Ignacio López Moreno

Instrument dimensions: tube inner diameter: 6.13 cm, 30cm^2 of surface, tube working length: 165 cm

Instrument description

The tube is made with clear Lexan, enabling the observation of the snow sample, with a total length of 165cm. Numbers are indicated every 5 cm and marks every centimeter. The edge has a 12 tooth cutter is made in steel, as well as two handles in the upper part to facilitate the introduction and extraction of the snow tube. The collected snow must be bagged and weighted separately.

Figure A7. SnowHydro

Description of default snow conditions for instrument usage

Can be used with most types of snow. Works best in relatively wet snow. It is particularly useful for snowpack ranging from 80 to 140 cm deep. If snow conditions are good and soil is no frozen, it may allow taking directly the snow sample with no need to dig a pit.

Possible error sources in default conditions

If snow is inconsistent part of the snow can be lost, we have also reported occasionally an excessive densification of the snow in the cutter preventing the entrance of more snow into the tube. The need to empty the snow in a bag is sometimes time consuming, especially when snow is sticky into the tube (often during warm air temperature but cold snowpack).

Possible error sources during the field campaign in Iceland

Snow was in general rather sticky.

General comments of the instrument usage during the field campaign in Iceland

Too long tube for the thin snowpack we found

8) Custom EV2 Italy

Name of the onserver(s): Roberto Sergio Azzoni, Antonella Senese

Instrument dimensions: 6 elements, 50 cm long (total 3 m); diameter 60 mm. Produced by the technical staff of prof. D. Bocchiola (Polytechnic of Milan, Italy)

Instrument description.

The snow tube is composed by 6 elements, each one 50 cm long. It is produced based on the characteristics of the Enel-Valtecne EV2 snow tube. However, this tube is made by aluminum (lighter than the Valtecne one) and the drilling tip is slightly different. The weighing of the tube can be performed directly on the field site thanks to an electronic weight scale and a proper support.

Figure A8. Composition of the snow tube. In the picture, there is only one of the total 6 elements of the tube.

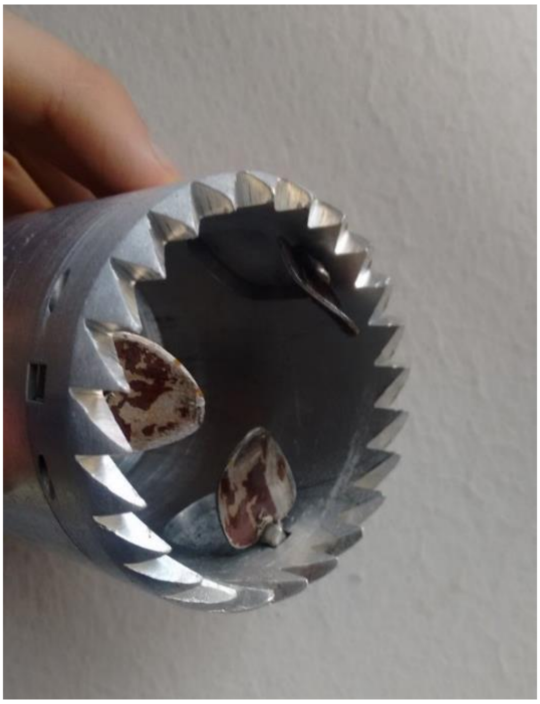

Figure A9. Detail of the drilling tip of the snow tube.

Figure A10. Field measurements with the snow tube.

Description of default snow conditions for instrument usage

This snow tube is mainly used by our team in the quantification of the snow accumulation on glaciers. Its characteristics permit to drill many typologies of snowpack. The presence of wide ice lens can be problematic because the drilling tip is not so greatly performing in this kind of snow layers.

Possible error sources in default conditions

A possible error source could be the underestimation of the snow water equivalent, in case that during the drilling some ice lenses are found and in this case they can be erroneously considered as the ground level (situation that can occur easier on glacier sites).

Possible error sources during the field campaign in Iceland

No error sources were identified during the field campaign. In the site next to the Geothermal, no problem occurred. Also in the ski area site, no problem occurred despite the extremely different characteristics and densities in the snowpack.

General comments of the instrument usage during the field campaign in Iceland

At all measurements in both sites (next to the Geothermal and ski area), the ground level was reached. In fact, we found a thin layer of tephra at the bottom of the snow core (removed before the weighting). Therefore, the results of the measurements can be considered correct. In addition, the fact that this device is composed by more elements allowed its easy use both with 50 cm of snow and with more than one meter. Indeed, next to the Geothermal we used two elements (totally 1 meter) and in the ski area three elements (1.5 meters).

Other comments

Even if it is composed by aluminum, there was not adhesion of the snow to the tube after each measurement and the emptying of the tube at the end of each drilling has been easy.

9) Enel-Valtecne EV2 Italy

Name of the observers: Roberto Sergio Azzoni, Antonella Senese

Instrument dimensions: 6 elements, 50 cm long (total 3 m); diameter 60 mm

Instrument description.

The Enel-Valtecne EV2 snow tube is composed by 6 elements (possibly even more), each one 50 cm long. The instrument can be used in different compositions in relation to the snow depth: from 1 element for <50 cm of snow to 6 elements for 3 m of snow, or even more elements for thickness >3 m. The tube is made by anodized stainless steel for limiting the cohesion between the snow and the steel after the measurements: in this way the emptying of the tube is fast. On both sides of the tube there are small openings that permit to control if the filling of the tube after the drilling is complete or is lacking. The robust drilling tip, made by stainless steel, permits to drill also the ice lens found in the snow pack. The drilling is performed also thanks to punch with the anti-rebound hammer that facilitates the perforation. The weighing of the tube can be performed directly on the field site thanks to an electronic weight scale and a proper support.

Figure A11. The Enel-Valtecne EV2 snow tube. From left: 4 elements of the tube, the drilling tip, the support for the weighing and the two wrenches for disassembling the tube after drilling operations

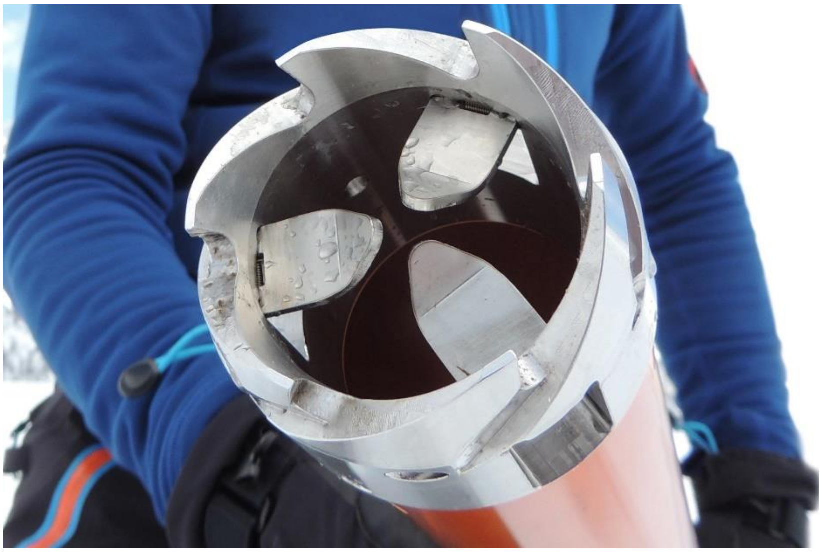

Figure A12. Detail of the drilling tip. The three small spring-wings permit to maintain the snow inside the tube after the perforation.

Figure A13. Field measurements with the Enel-Valtecne EV2 snow tube.

Description of default snow conditions for instrument usage

The characteristics (strength and typology of the drilling tip) permit to drill the most of snowpack conditions, even in presence of ice lens or dense firn. In particular, our team uses this instrument for the quantification of the snow water equivalent on glaciers, at the end of the accumulation period (April) when the snow metamorphosis (higher density) occurs.

Possible error sources in default conditions

No particular error sources have been identified in default conditions.

Possible error sources during the field campaign in Iceland

In the site next to the Geothermal, the limited snowpack thickness and the low density and weight of the snow (fresh snow) could slightly affect the measurements.

General comments of the instrument usage during the field campaign in Iceland

At all measurements in both sites (next to the Geothermal and ski area), the ground level has been reached; in fact, we have found a thin layer of tephra at the bottom of the core (removed before the weighting). Therefore, the results of the measurements can be considered correct. In addition, the fact that this device is composed by more elements allowed its easy use both with 50 cm of snow and with more than one meter. Indeed, next to the Geothermal we used two elements (totally 1 meter) and in the ski area three elements (1.5 meters).

Other comments

The anodized stainless steel has prevented the adhesion of the snow to the tube after each measurement and the emptying of the tube at the end of each drilling has been easy. The use of the anti-rebound hammer favors the penetration of the tube also in the denser layers of the snowpack that have been found in the second site (ski area).

10) Federal Sampler USA

Name of the observers: Steven R Fassnacht

Instrument dimensions: 2 to 7+ elements, 76 cm long each (total 153 to 533+ cm); diameter 38.1 mm

References:

Beaumont, R.T., and R. A. Work, 1963. Snow Sampling Results from Three Samplers. Hydrological Sciences Journal, 8:4, 74-78, doi: 10.1080/02626666309493359.

Clyde, G.D., 1932. Utah Snow Sampler and Scales for Measuring Water Content of Snow. Utah State University, Utah Agricultural Experiment Station, UAES Circulars Paper 90.

Natural Resources Conservation Service, no date. The history of Church: how NRCS' snow survey program got started. U.S. Department of Agriculture, URL: <https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/home/?cid=NRCSEPRD329084>.

Soil Conservation Service, 1959. Snow-Survey Sampling Guide. U.S. Department of Agriculture, Agriculture Handbook No. 169, U.S. Government Printing Office, Washington DC URL: <https://naldc.nal.usda.gov/catalog/CAT87208787>.

Instrument description and use.

The Federal Sampler is the standard snow corer used across the United States by the Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service. It or it predecessor the Mount Rose sampler, developed in the early 1900s by Professor James Church, has been in use by the NRCS since the snow course network was established across the Western United States in the mid-1930s.

The Federal Sampler consists of 76 cm (30 inch) segments (Figure 10-1) of 38 mm (1.5 inch) diameter tubes that can be screwed together to any length desired. It is designed for use in deeper snowpack, usually deeper than 1-m; in the Mount Rose area of the eastern Californian Sierra Nevada, peak snow depths can be 3 to 5 meters. At least two sections (152 cm) of tube must be used.

Once assembled, the empty Federal Sampler is weighed on a spring scale that holds a cradle, as is done with many other snow corers (Figure A14). The tare of the sampler is measured to the nearest half inches (12.7 mm) of SWE. The sampler is "screwed" into the snowpack to cut (Figure A15) through possible layers. Once the ground/soil layer is reached, the depth of snow is measured on the side of the sampler to the nearest half inches (12.7 mm). Then the sampler is given a sharp twist to cut into the soil to add a soil plug to keep the snow from leaving the sampler as it is extracted from the snowpack. In continental climates, such as Colorado, there is often 30 to 80 cm of cohesionless depth hoar at the bottom of the snowpack that falls out of the sampler when there is no soil plug. Once the sampler is extracted, the length of the core is record to the nearest half inches (12.7 mm). If the ratio of length of snow core to snow depth is less than 70%, it is assumed that an incomplete sample has been extracted and the snow core sample is discarded. An adequate snow core is weighed and the tare plus SWE is recorded. The SWE and snow depth values are used to compute density. For a snow course, there are typically 10 sets of snow samples measured along a transect.

After the sample is extracted from the snowpack and weighed, it is discarded by dumping the sample out of the non-cutting end. There are slots along the sampler (Figure A14) that are used to clean the snow out of the sampler.

Instrument photographs

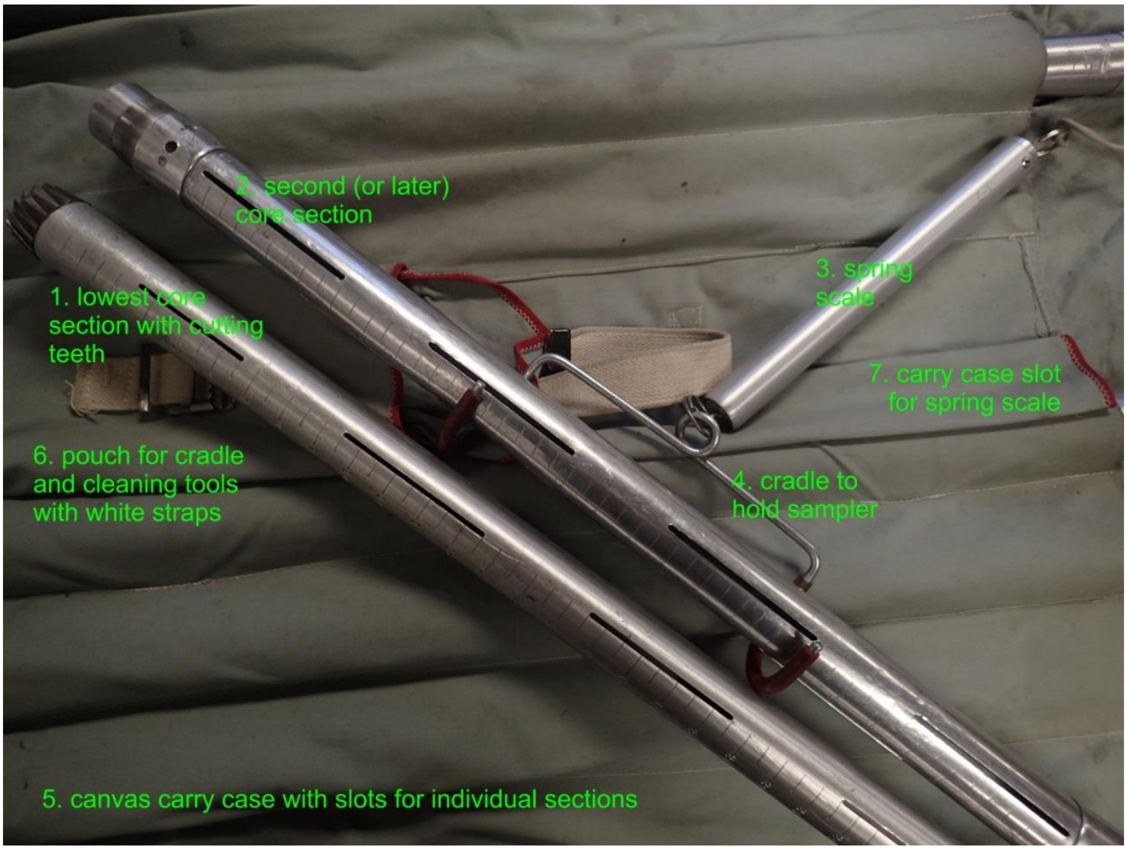

Fig. A14: The Federal Sampler snow tube with the various components labelled.

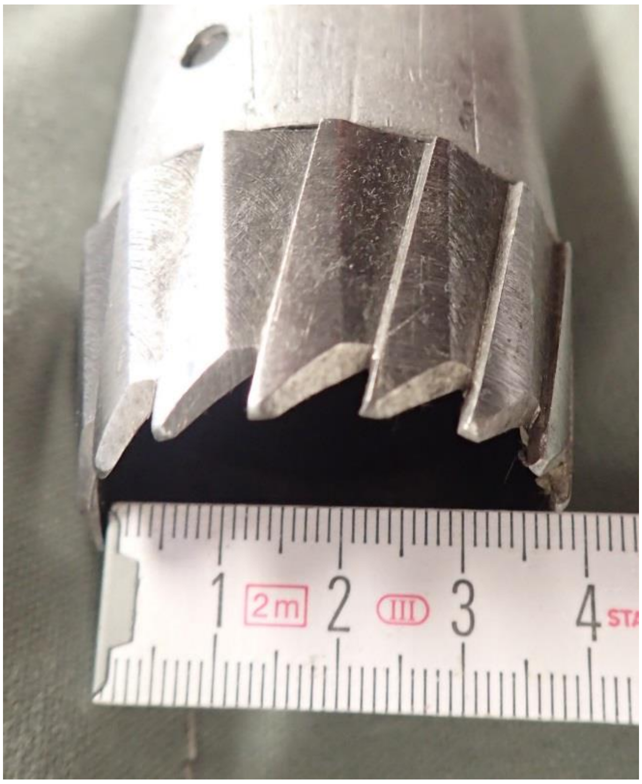

Fig. A15: Detailed image of the Federal Sampler cutting teeth.

Fig. A16: Sequence of using the Federal Sampler from Cameron Pass in Northern Colorado collected by Ralph Parshall and a colleague in 1941 (from <https://dspace.library.colostate.edu/handle/10217/172789>).

Description of default snow conditions for instrument usage

The Federal Sampler is designed to measured SWE and depth for the most of seasonal snowpack conditions, including ice layers. It is used operationally at over 2000 snow course locations across the Western United States and Western Canada. Measurements are usually taken around the first of the month from January or February through April or May. Some snow courses have been running continuously from 1936.

Possible error sources in default conditions

There are two issues with the sampler. The first is use in shallow snowpacks due to the sampler diameter (Figure A15) or light (new) snow conditions The second is melting and refreezing of snow. The sampler is fabricated from aluminum.

Possible error sources during the field campaign in Iceland

It is possible that at Bláfjöll site, the cutting teeth could not cut into the lava rock as there was no soil. This may have led to a reduced sample being extracted.

Other comments

This is a sampler that requires much practice. The usage principle is easy and similar to many of the other samplers, but inexperienced users often extract snow cores that are too short, i.e., not representative of the snowpack. Melting of snow inside the sampler due to sunlight shining of the sampler, and subsequent refreezing when the sampler is inserted into a colder than freezing (non-melting) snowpack.