Geosci. Instrum. Method. Data Syst. Discuss., 5, 405–426, 2015
www.geosci-instrum-method-data-syst-discuss.net/5/405/2015/
doi:10.5194/gid-5-405-2015

Geoscientific Instrumentation Methods and Data Systems Discussions

Open Access

Sodankylä manual snow survey program

L. Leppänen[1], A. Kontu[1], H.-R. Hannula[1], H. Sjöblom[2], and J. Pulliainen[1]

[1]Finnish Meteorological Institute, Arctic Research, Sodankylä, Finland
[2]Finnish Environment Institute, Helsinki, Finland

Received: 27 November 2015 – Accepted: 27 November 2015 – Published: 10 December 2015

Correspondence to: L. Leppänen (leena.leppanen@fmi.fi)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The manual snow survey program of the Arctic Research Centre of Finnish Meteorological Institute (FMI-ARC) consists of numerous observations of natural seasonal taiga snowpack in Sodankylä, northern Finland. The easily accessible measurement areas represent the typical forest and soil types in the boreal forest zone. Systematic snow measurements began in 1909 with snow depth (SD) and snow water equivalent (SWE); however some older records of the snow and ice cover exists. In 2006 the manual snow survey program expanded to cover snow macro- and microstructure from regular snow pits at several sites using both traditional and novel measurement techniques. Present-day measurements include observations of SD, SWE, temperature, density, horizontal layers of snow, grain size, specific surface area (SSA), and liquid water content (LWC). Regular snow pit measurements are performed weekly during the snow season. Extensive time series of manual snow measurements are important for the monitoring of temporal and spatial changes in seasonal snowpack. This snow survey program is an excellent base for the future research of snow properties.

1 Introduction

Snow is an important parameter in meteorological and climatological research because of its high albedo, thermal insulation properties, and water content (Groisman et al., 1994; Cohen and Rind, 1991). Snow has a large effect on global water cycle and ecology, in addition to social aspects, as a water reservoir (van Dijk et al., 2014; Barnett et al., 2005). Moreover, seasonal snow cover can be used as a proxy for monitoring the effects of climate change (Hernández-Henríquez at al., 2015). The most important observed snow cover parameters are snow water equivalent (SWE), snow extent (SE), and snow depth (SD). In many applications, remote sensing is used for global daily observations. However, automatic weather station observations and manual measure-

GID
5, 405–426, 2015

ments have still an important role in snow monitoring, especially in numerical weather prediction (NWP) systems (e.g. de Rosnay et al., 2014) and hydrological monitoring.

Many snow properties can be measured automatically, but manual measurements are still vital for the exact observations of snow structure. Snow microstructure is defined with such grain related properties as size, shape, orientation and bonding. Snowpack consists of horizontal layers having varying micro- and macrostructural properties (Colbeck, 1991). Grain metamorphism changes snow microstructure, and is driven mainly by temperature differences and pressure of the upper snowpack (Colbeck, 1982). Therefore, vertical changes of macrostructural parameters, such as temperature and density, are related to the evolution of snow microstructure. However, the structure of snowpack is very complex and spatial variations are large even in a small scale (Rutter et al., 2014; Derksen et al., 2009). Therefore, manual observations of snow macro- and microstructure have an important role in the monitoring of temporal evolution and spatial variations of snowpack.

This paper introduces the manual snow survey program, the long-standing and present-day manual observations of natural seasonal snowpack, at the Arctic Research Centre of Finnish Meteorological Institute (FMI-ARC). Measurements started in 1909 with SWE and SD observations. The extent of manual snow measurements has constantly grown. In 2006 regular snow pit measurements of snow macro- and microstructure began, at first in smaller scale and later on with additional modern measurement techniques. Sodankylä manual snow survey program aims at studying the spatial and temporal variability of snowpack in varying environmental conditions typical to the boreal forest zone, including pine and spruce forests, open bogs, and lake ice. The data set is also important as a reference for development of remote sensing instruments and interpretation algorithms.

2 Site and history

The FMI-ARC station is located in 67.368° N, 26.633° E, 7 km south of Sodankylä town centre. A map of the research station area and surroundings, including the manual snow measurement sites, is shown in Fig. 1. Pictures from the measurement sites are shown in Fig. 2.

Based on 30 year (1981–2010) meteorological records (Pirinen et al., 2012), the first snow typically falls in Sodankylä in October, while snow melt-off takes place in mid-May. The snow maximum of about 80 cm occurs in late March. The snow class is taiga (Sturm and Holmgren, 1995).

Synoptic weather observations have been made in the research station area since 1908 and systematic manual snow measurements began in 1909. FMI archives contain some observations of snow and ice cover (e.g. first snow, SD, soil frost depth, snowfall events) from several locations in Finland, including Sodankylä, beginning in 1891, but these are still mostly not inventoried nor digitized. Today two institutes share the research station in Sodankylä: Sodankylä Geophysical Observatory (SGO) which was established in 1913 and FMI observatory which was established in 1949.

3 Data sets

3.1 Snow density, depth and SWE

There are two long time series of snow density, depth and SWE: (1) between years 1909 and 1953 at a single measurement site and (2) an on-going data set starting in 1972 at two sites. Until 2002, measurements were performed in the morning of 5th, 10th, 15th, 20th, 25th, and the last day of every month, if there was snow on the ground. From 2002 onwards there are measurements only in January and March.

The data set from 1909–1953 was measured by SGO. The exact measurement site is unknown, but it was on the research station area. The second data set from 1972

GID
5, 405–426, 2015

onwards is measured by FMI from two measurement sites: an open area, which today is on the premises of Sodankylä airport (Fig. 2c), and a fenced site in a forest at the research station area (Fig. 2d). In addition to two SWE measurements, SD at five fixed stakes is recorded at both sites (in 1972–1976, 9 stakes and two SWE measurements in the open area, 25 stakes and four SWE measurements in the forest area).

Before the 1940's, SWE was measured by coring a cylindrical sample of snow with a tube of 100 cm^2 cross-sectional area, melting the snow in a covered bucket, and measuring the volume of meltwater. From the 1940's, a special scale calibrated to show SWE has been used to weight the cored snow sample (Fig. 4e). There is a SD scale on the outside of the sampling tube; snow density can be calculated from SD and SWE.

All SWE and SD measurements from 1972 onwards have been digitized and are available from FMI-ARC on request. Most of the earlier measurements are only in paper form but the digitizing work is on-going.

3.2 Daily snow depth

A daily time series of SD in Sodankylä exists from 1 January 1911 onwards, with the exception of the year 1913, which is mostly missing. These data have been collected from many sources and possibly several measurement sites on open areas at the research station area. Since 1949 SD is measured at Sounding station (Fig. 1). Despite the changes in measurement location, the data set represents the best knowledge of long-standing snow depth conditions in Sodankylä. Last manual synoptic observations were made in December 2008, and afterwards there are only automatic SD measurements. Digitized SD data are available from FMI-ARC on request.

Mean, minimum and maximum of SD for each day of year are shown in Fig. 3 for years 1911–2014. The figure shows the large variation of snow cover between years: continuous snow has fallen earliest on day 261 (year 1998) and latest on day 348 (year 2000). The last day of snow on the ground in spring has varied from day 114 (year 1937) to day 166 (year 1911). The maximum of the mean SD curve is 72 cm on day

GID
5, 405–426, 2015

90; minimum SD on this day is 43 cm and maximum is 106 cm. The absolute maximum SD in this data set is 119 cm (on 6 April 2000).

3.3 Snow course

Finnish Environment Institute (SYKE) maintains a network of 150 snow courses in Finland, one of which is located around FMI-ARC station in Sodankylä and measured by FMI personnel. Usually, there are 80 SD and 8 SWE measurements made at regular intervals along a 4 km course which covers terrain, vegetation and land covers typical to the area. The measurement locations are divided into six categories: open area, forest opening, pine-dominated forest, spruce-dominated forest, broadleaf-dominated forest, and open bog. The Sodankylä snow course covers all of these except open area, the most common being bog and spruce forest. The snow course measurements represent the variation in general snow conditions on the area and in each category.

Snow course measurements of SYKE and FMI in Finland began in the 1930's. The Sodankylä snow course measurements began in around 1959 by FMI. Before 1991, the snow course was measured in the middle of the month in January and March. In 1991–1996 the course was measured in the beginning and middle of every month during the snow season, and after 1996 the course is measured in the middle of every month. Moreover, in 2009–2014 FMI-ARC measured the Sodankylä snow course and an additional course in Tanhua (50 km northeast of Sodankylä) at the turn of the month.

The average SWE of the Sodankylä snow course is available from the OIVA database (www.ymparisto.fi/oiva) of the Finnish environment authorities from 1991 onwards. Since 1991 the SWE, SD and density values for separate measurement spots and averages for each category are available from SYKE on request. The additional snow course measurements by FMI-ARC in 2009–2014 are available from FMI-ARC on request. The Sodankylä snow course measurements before 1991 are not digitized and available only in paper form.

GID
5, 405–426, 2015

3.4 Snow pit observations

Locations of the regular snow pit observation areas are permanent year after year in the measurement sites. Snowpack is disturbed as little as possible, thus passage to measurement area is limited to one track. New snow pit is dug at least ~ 50 cm away from the old one towards the undisturbed area. This procedure establishes temporally comparable observations. Spatial variability is unaccounted for because features of the area are assumed to remain constant.

Regular snow pit measurement includes definition of horizontal layers, fast visual estimation of grain size (E according to Fierz et al. (2009)) and type (every layer), post processed traditional grain size (E and E_{max}) and grain type from macro-photographs (every layer), specific surface area (SSA) profile (3 cm interval), density profile (5 cm interval), density and liquid water content (LWC) profile (10 cm interval), temperature profile (10 cm interval), bulk SWE, and SD. Detailed description of the parameters and used instrumentation is in following chapter. Starting years of the observations with different instruments are presented in Table 1. Photographs from the measurement sites are in Fig. 2 and photographs of measurements and equipment are in Fig. 4. Snow pit data are available from FMI-ARC on request.

3.4.1 Equipment and description of measurements

Horizontal layers of the snowpack are defined visually from hardness, grain size and grain type differences with the help of a paintbrush (for removing very soft layers, Fig. 4a) and tooth picks (for detecting thin hard layers). From every layer, macro-photographs of snow grains are taken against a 1 mm reference plate using digital camera and self-made stable stand. Typical grains from each layer are photographed so that the grains are separated on the plate as well as possible without breaking them (Fig. 4f). Photographs are analysed later, and largest extent of an average grain E, as well as that of largest grains E_{max} (Fierz et al., 2009), is evaluated visually with 0.25 mm resolution. It is possible to measure the size of a single grain with much higher reso-

GID
5, 405–426, 2015
Sodankylä manual snow survey program
L. Leppänen et al.

lution, but practise has shown that error arising from multiple observers defining the average value for a layer is of this magnitude. Process is described more closely by Leppänen et al. (2015).

Microstructural parameter SSA is the ratio between surface area of ice and its mass in the snow sample (Legagneux et al., 2002). It describes the area of snow grain surface, which is straightforward to define, while grain size has multiple definitions (Fierz et al., 2009; Pirazzini et al., 2015; Aoki et al., 2000). Optical grain size can be derived from SSA by assuming the grains to be spheres (Gallet et al., 2009). Recently developed method for determining SSA is to measure the reflectance of infrared radiation from a snow sample (Gallet et al., 2009, Fig. 4c). The IceCube instrument (Fig. 4d) is similar to DUFISSS presented by Gallet et al. (2009), but it uses only 1310 nm wavelength for reflectance measurements. At FMI-ARC, IceCube has been used and optical grain size data are available since 2012.

LWC describes the amount of liquid water in the snowpack, and it is usually observed by measuring the electrical conductivity of snow. The snow fork instrument (Sihvola and Tiuri, 1986, Fig. 4b), measures the dielectricity of snow between two metal rods and outputs real and imaginary permittivity, which are used to derive density and LWC.

Manual density profile is measured with a 250 mL wedge sampler (RIP2 cutter from SnowMetrics) or a self-made 500 mL rectangular sampler, and a string balance or digital scale. Temperatures are measured with Milwaukee TH310 thermometers. The $\sim$ 10 cm long probe of the thermometer is inserted horizontally completely into snowpack.

Bulk SWE from whole snowpack is measured by weighting a snow sample cored with a self-made 70 cm high tube with a special scale calibrated to show SWE (see Sect. 3.1, Fig. 4e). SD is measured with a stake and the value is averaged from three measurement spots around the snow pit.

GID
5, 405–426, 2015

3.4.2 Measurement sites

Intensive Observation Area

The main present-day measurement site is the Intensive Observation Area (IOA). The IOA consists of a forest clearing (diameter about 40 m) and the sparse pine forest around it as shown in Fig. 2a. Sparse pine-dominated conifer forest is the most common land cover type in northern Finland. Vegetation in the opening is mainly very low lichen and some heather. Wind has a minimal effect on snow accumulation. The measurement site was established in 2006 and today it hosts numerous automatic snow measurements: snow temperature profile, SD, precipitation from disdrometer, brightness temperature with microwave radiometers (1.4, 10.6, 18.7, 21, 36.5, 89 and 150 GHz frequency channels), broadband albedo, and spectral albedo. In addition, several measurement campaigns have been performed at the IOA with variable instrumentation for snow measurements. Most of the automatic measurements, as well as the manual snow pits, are located in the forest clearing. Snow pit measurements are made regularly (2–4 times per month during the snow season) since 2006.

Bog site

Bogs are the second most common land cover type in the northern Finland. The bog site is located about 1 km northeast from the IOA. Water level at the moss-covered peatbog varies due to precipitation and time of year; every spring during and after snowmelt the bog site is completely submerged, but the autumn conditions might range from completely submerged to completely dry. Typically snow accumulates over a smooth ice layer, which is infrequently penetrated by low vegetation (grass and twigs). Wind affects snow accumulation and surface level as well as macro- and microstructure of the snowpack. Automatic observations of SD, SWE, broadband albedo, and snow temperature profile are made. Manual snow pit measurements were made regularly (2–4 times per month) in 2009–2015.

GID
5, 405–426, 2015

Lake Orajärvi

Lake Orajärvi is located 10 km east from FMI-ARC. SD variations over the lake ice are large and mainly caused by heavy wind, which also influences snow macro- and microstructure significantly. Typically water rises through cracks in the ice during the winter and refreezes over the solid ice. Often the bottom of the snowpack is wet. Ice measurements (ice depth, ice layers and SD) are made regularly from three fixed spots. The site has no automatic measurements. Snow pit measurements were made regularly (once or twice per month) in 2008–2014.

3.4.3 Example data

Minimum, maximum and mean of yearly SD, density and grain size (E) values from the snow pit measurements are presented in Table 2 for the sites IOA, bog site and Lake Orajärvi. Mean SD is largest at IOA and smallest at Lake Orajärvi. Maximum SD varied between 65.3–105.6 cm at IOA, 79.6–54.0 cm at bog site and 23–44 cm at Lake Orajärvi. Usually, density is largest at Lake Orajärvi. Mean density varied between 203–207 kg m^{-3} at IOA, 180–234 kg m^{-3} at bog site and 200–280 kg m^{-3} at Lake Orajärvi. Minimum E varies between 0–0.25 mm, maximum E between 2.5–6 mm, and mean E between 0.7–2.1 mm. Bog site and Lake Orajärvi become unpassable during the melting period, and therefore those measurements are usually finished before measurements at IOA.

Profiles of snow properties from a single snow pit 12 March 2013 are presented in Fig. 5. Total SD was 82 cm. Density varied between 92–324 kg m^{-3}, having an average value 272 kg m^{-3}. Temperature varied between −17.4 and −5.4 °C, so that temperature was closest to 0 °C at the bottom of the snowpack. E varied between 0.25–2.25 mm, and E was largest at the bottom of snowpack. SSA was largest at the surface 81 m^2 kg^{-1} and smallest 9 m^2 kg^{-1} at depth 20 cm. Values and trends are typical for snow pits in March.

GID
5, 405–426, 2015

3.5 Lake ice observations

Ice thickness is monitored in three locations 20 m apart on Lake Orajärvi. The measurement site is 400 m from the nearest shore and away from the snow mobile tracks crossing the lake. The measurements follow the lake ice monitoring protocol of the Finnish Environment Institute, but are not part of the official measurement network. Data are available from FMI-ARC on request.

Three SD measurements are made at each of the three locations. A hole is drilled almost through the ice. The layers of hard ice and refrozen ice are detected, as well as possible water layers inside the ice. Then the hole is drilled completely through the ice, and ice thickness is measured using a stake with a hook at the end. In 2008–2014 a snow pit was measured at the first drill site. A photograph from ice thickness measurements on Lake Orajärvi is shown in Fig. 2e.

Time series of mean ice thickness and SD on Lake Orajärvi are shown in Fig. 6. Maximum ice thickness of 60 to 76 cm is reached in April in the last measurements before snowmelt. Maximum SD on ice varies between 20 and 35 cm. Typically SD decreases close to 0 cm in the last measurements of the season, as snow and water on ice freeze on top of the ice layer.

4 Summary

The Sodankylä manual snow survey program includes manual measurements of natural seasonal snowpack in northern Finland. Measurements are performed at several divergent measurement sites at FMI-ARC. The station is equipped with a comprehensive set of tools for the manual measurements of snow and extensive reference instrumentation for automatic snow measurements and meteorological measurements. Measurements of SD and SWE are made since 1909, and exact observations of snow macro- and microstructure are made since 2006 from the snow pits. The pit measurements include observations of e.g. horizontal layers, grain size, SSA, LWC, density,

GID
5, 405–426, 2015

temperature, SWE and SD. This paper presents a summary of the collected data sets. Collected observations are also reference data for the remote sensing applications.

Data availability

All the FMI manual measurements presented in this paper are available from FMI-ARC on request (e.g. by e-mail to leena.leppanen@fmi.fi, anna.kontu@fmi.fi or henna-reetta.hannula@fmi.fi). The averages of the SYKE snow course data are available from the OIVA database (www.ymparisto.fi/oiva), and full measurement data from SYKE on request (e.g. by e-mail to heidi.sjoblom@ymparisto.fi).

Acknowledgements. We thank the personnel of FMI-ARC who participated in the manual snow measurements. Ms. Anita Sassali and Ms. Hanne Suokanerva are acknowledged for digitizing the long-standing measurements. The manuscript preparation was supported by the EU 7th Framework Program project "European-Russian Centre for cooperation in the Arctic and Sub-Arctic environmental and climate research" (EuRuCAS, grant 295068).

References

Aoki, T., Aoki, T., Fukabori, M., Hachikubo, A., Tachibana, Y., and Fumihiko, N.: Effects of snow physical parameters on spectral albedo and bidirectional reflectance of snow surface, J. Geophys. Res.-Atmos., 105, 10219–10236, 2000.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303–309, 2005.

Cohen, J. and Rind, D.: The effect of snow cover on the climate, J. Climate, 4, 689–706, 1991.

Colbeck, S. C.: An overview of seasonal snow metamorphism, Rev. Geophys. Space Ge., 20, 45–61, 1982.

Colbeck, S. C.: The layered character of snow covers, Rev. Geophys., 29, 81–96, 1991.

de Rosnay, P., Balsamo, G., Albergel, C., Muñoz-Sabater, J., and Isaksen, L.: Initialisation of land surface variables for numerical weather prediction, Surv. Geophys., 35, 607–621, 2014.

Derksen, C., Sturm, M., Liston, G. E., Holmgren, J., Huntington, H., Silis, A., and Solie, D.: Northwest territories and Nunavut snow characteristics from a subarctic traverse: implications for passive microwave remote sensing, J. Hydrometeorol., 10, 448–463, 2009.
Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., Nishimura, K., Satyawali, P. K., and Sokratov, S. A.: The International Classification for Seasonal Snow on the Ground, IHP-VII Technical Documents in Hydrology N°83, IACS Contribution N°1, UNESCO-IHP, Paris, 2009.
Gallet, J.-C., Domine, F., Zender, C. S., and Picard, G.: Measurement of the specific surface area of snow using infrared reflectance in an integrating sphere at 1310 and 1550 nm, The Cryosphere, 3, 167–182, doi:10.5194/tc-3-167-2009, 2009.
Groisman, P. Y., Karl, T. R., Knight, R. W., and Stenchikov, G. L.: Changes of snow cover, temperature, and radiative heat balance over the Northern Hemisphere, J. Climate, 7, 1633–1656, 1994.
Hernández-Henríquez, M. A., Déry, S. J., and Derksen, C.: Polar amplification and elevation-dependence in trends of Northern Hemisphere snow cover extent, 1971–2014, Environ. Res. Lett., 10, 044010, doi:10.1088/1748-9326/10/4/044010, 2015.
Legagneux, L., Cabanes, A., and Dominé, F.: Measurement of the specific surface area of 176 snow samples using methane adsorption at 77 K, J. Geophys. Res.-Atmos., 107, 4335, doi:10.1029/2001JD001016, 2002.
Leppänen, L., Kontu, A., Vehviläinen, J., Lemmetyinen, J., and Pulliainen, J.: Comparison of traditional and optical grain-size field measurements with SNOWPACK simulations in a taiga snowpack, J. Glaciol., 61, 151–162, 2015.
Pirazzini, R., Räisänen, P., Vihma, T., Johansson, M., and Tastula, E.-M.: Measurements and modelling of snow particle size and shortwave infrared albedo over a melting Antarctic ice sheet, The Cryosphere Discuss., 9, 3405–3474, doi:10.5194/tcd-9-3405-2015, 2015.
Pirinen, P., Simola, H., Aalto, J., Kaukoranta, J.-P., Karlsson, P., and Ruuhela, R.: Climatological Statistics of Finland 1981–2010, Finnish Meteorological Institute Reports, 1, 2012.
Rutter, N., Sandells, M., Derksen, C., Toose, P., Royer, A., Montpetit, B., Langlois, A., Lemmetyinen, J., and Pulliainen, J.: Snow stratigraphic heterogeneity within ground-based passive microwave radiometer footprints: implications for emission modeling, J. Geophys. Res.-Earth, 119, 550–565, 2014.
Sihvola, A. and Tiuri, M.: Snow fork for field determination of the density and wetness profiles of a snow pack, IEEE T. Geosci. Remote, 24, 717–721, 1986.

GID
5, 405–426, 2015

Sodankylä manual snow survey program

L. Leppänen et al.

Sturm, M. and Holmgren, J.: A seasonal snow cover classification system for local to global applications, J. Climate, 8, 1261–1283, 1995.
van Dijk, A. I. J. M., Renzullo, L. J., Wada, Y., and Tregoning, P.: A global water cycle reanalysis (2003–2012) merging satellite gravimetry and altimetry observations with a hydrological multi-model ensemble, Hydrol. Earth Syst. Sci., 18, 2955–2973, doi:10.5194/hess-18-2955-2014, 2014.

Table 1. Available manual snow measurement data from different sites and instruments. Different data sets are bolded and more detailed information of data and dates is marked with non-bolded font.

Date	Site	Frequency	Data
1911–	**Sodankylä**	**Daily**	**SD**
1972–	**Airport**	**5 days**	**SD, density and SWE**
1972–	**Forest**	**5 days**	**SD, density and SWE**
1991–	**Sodankylä**	**Monthly**	**SD and SWE course**
2006–	**IOA**	**2–4 month^{-1}**	**Snow pit measurements**
2006–			SD, layers, grain size (E) profile, temperature profile
2007–			SWE, density
2009–			Density profile, LWC profile
2012–			SSA profile
2008–2014	**Lake Orajärvi**	**1–2 month^{-1}**	**Snow pit measurements**
2008–2014			SD, SWE, layers, grain size (E) profile, temperature profile, density
2009–2014			Density profile, LWC profile
2008–	**Lake Orajärvi**	**1–2 month^{-1}**	**Ice thickness and SD**
2008–			Thickness of ice, refrozen slush and water layers, SD
2009–2015	**Bog**	**2–4 month^{-1}**	**Snow pit measurements**
2009–2015			SD, SWE, layers, grain size (E) profile, temperature profile, density (bulk and profile), LWC profile

GID
5, 405–426, 2015

Table 2. Yearly minimum, maximum and mean values of SD, density and grain size (E) for the snow pit measurements. Measurement sites are IOA, bog and Lake Orajärvi (ora). SD is average of three measurements, density is calculated from the bulk SWE measurements, and E is evaluated from the macro-photographs.

	Site	SD min (cm)	SD max (cm)	SD mean (cm)	Density min ($kg\,m^{-3}$)	Density max ($kg\,m^{-3}$)	Density mean ($kg\,m^{-3}$)	E min (mm)	E max (mm)	E mean (mm)
2006–2007	IOA	6.0	63.0	34.20	–	–	–	0.25	8.00	2.10
2007–2008	IOA	18.0	93.0	50.97	127	281	219	0.00	6.00	1.73
2008–2009	IOA	4.0	65.3	42.39	132	322	215	0.00	3.00	0.89
2008–2009	ora	5.0	26.6	15.00	213	335	280	0.25	1.50	0.79
2009–2010	IOA	9.6	105.6	51.83	95	365	215	0.25	3.50	1.18
2009–2010	bog	1.0	78.3	29.28	85	600	219	0.25	5.00	1.23
2009–2010	ora	2.0	43.3	17.78	173	350	235	0.25	2.50	1.12
2010–2011	IOA	9.0	75.0	44.02	80	423	203	0.25	4.00	1.19
2010–2011	bog	2.0	54.0	29.88	0	433	180	0.25	5.00	1.32
2010–2011	ora	1.5	44.0	19.97	85	700	215	0.25	5.00	1.18
2011–2012	IOA	4.0	81.3	53.31	93	430	225	0.25	2.50	0.88
2011–2012	bog	1.3	79.6	46.74	112	486	234	0.10	2.50	1.01
2011–2012	ora	6.0	30.0	18.66	128	393	241	0.25	2.50	0.91
2012–2013	IOA	15.6	82.3	55.19	121	336	213	0.00	3.00	1.08
2012–2013	bog	1.3	65.0	38.08	120	371	195	0.25	4.00	1.06
2012–2013	ora	16.0	32.3	20.57	170	233	200	0.25	4.00	1.42
2013–2014	IOA	8.0	81.0	49.67	167	358	227	0.25	3.00	1.02
2013–2014	bog	11.6	55.0	35.88	158	407	228	0.25	3.25	1.12
2013–2014	ora	4.6	23.0	14.57	135	367	239	0.25	2.50	1.02
2014–2015	IOA	21.3	78.3	55.12	131	417	211	0.20	2.50	0.92
2014–2015	bog	14.0	71.0	47.36	105	471	234	0.20	3.00	1.12

GID
5, 405–426, 2015
Sodankylä manual snow survey program
L. Leppänen et al.

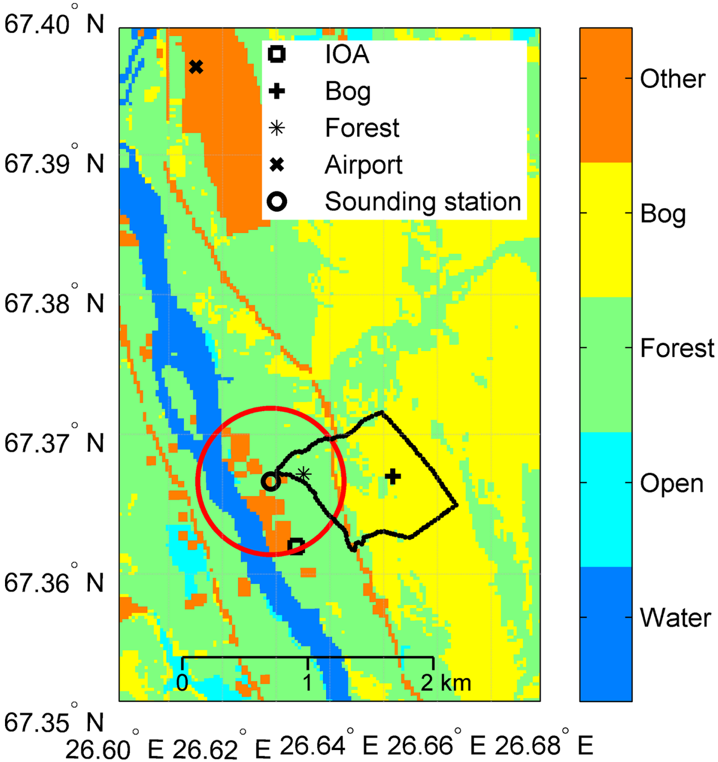

Figure 1. Map of FMI-ARC area and the manual snow measurement sites: airport (x), sounding station (o), forest fence (*), bog snow pit (+), IOA snow pit (square), snow course (black line). The approximate research station area is marked with a red circle.

GID
5, 405–426, 2015

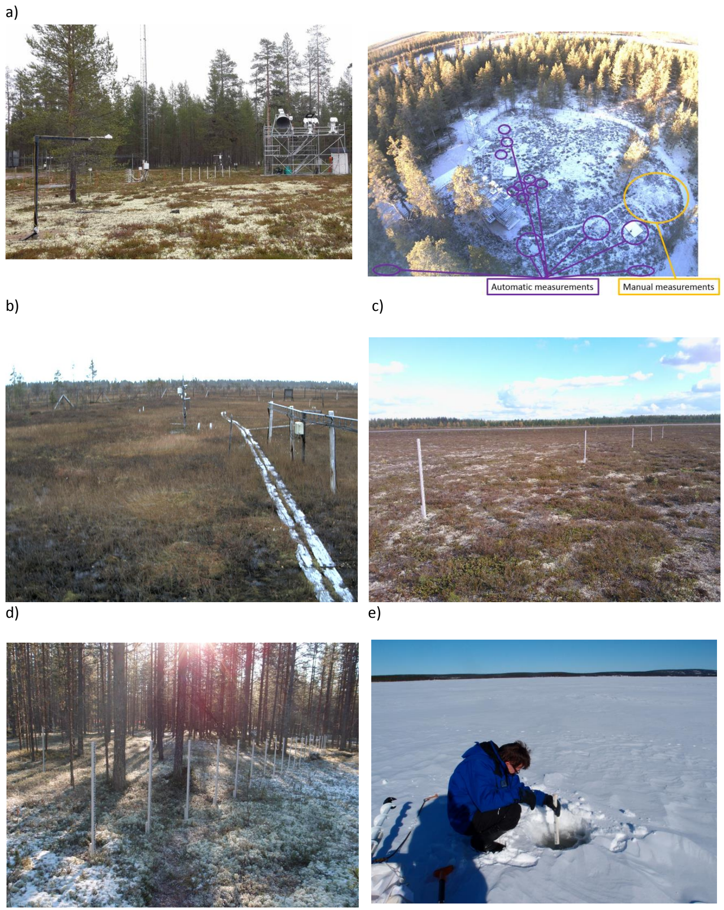

Figure 2. Snow measurement sites: **(a)** IOA (purple – automatic measurements, yellow – manual measurements), **(b)** bog site, **(c)** airport, **(d)** forest, **(e)** Lake Orajärvi.

GID
5, 405–426, 2015

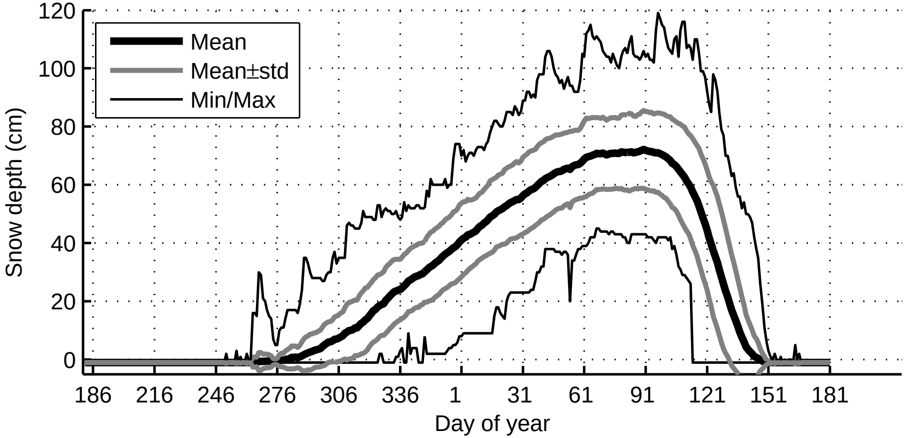

Figure 3. Mean, maximum and minimum SD for each day of year in Sodankylä in 1911–2014.

GID
5, 405–426, 2015

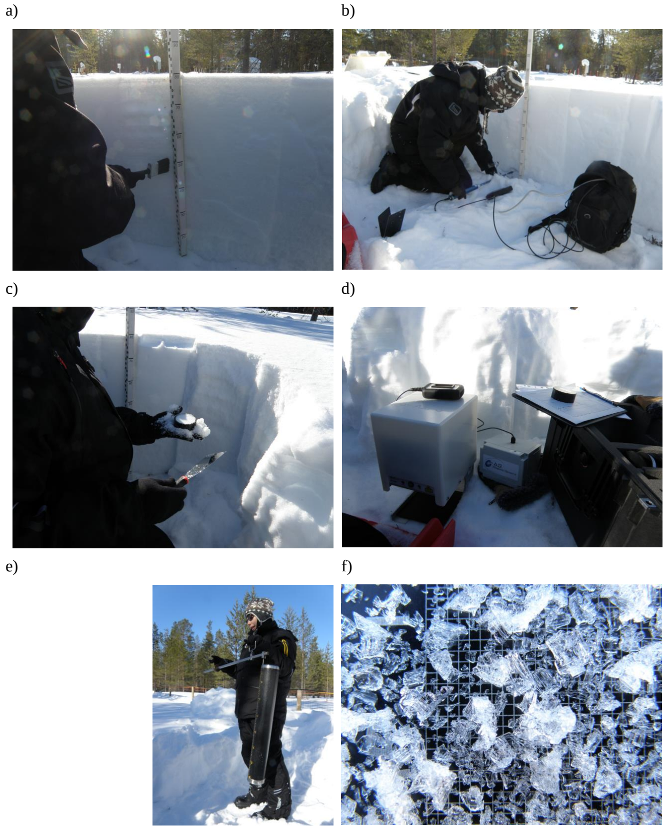

Figure 4. Pictures of snow pit measurements: **(a)** determining layers, **(b)** snow fork, **(c)** snow sample for IceCube, **(d)** IceCube instrument, **(e)** bulk SWE measurement, **(f)** depth hoar snow grains on 1 mm grid.

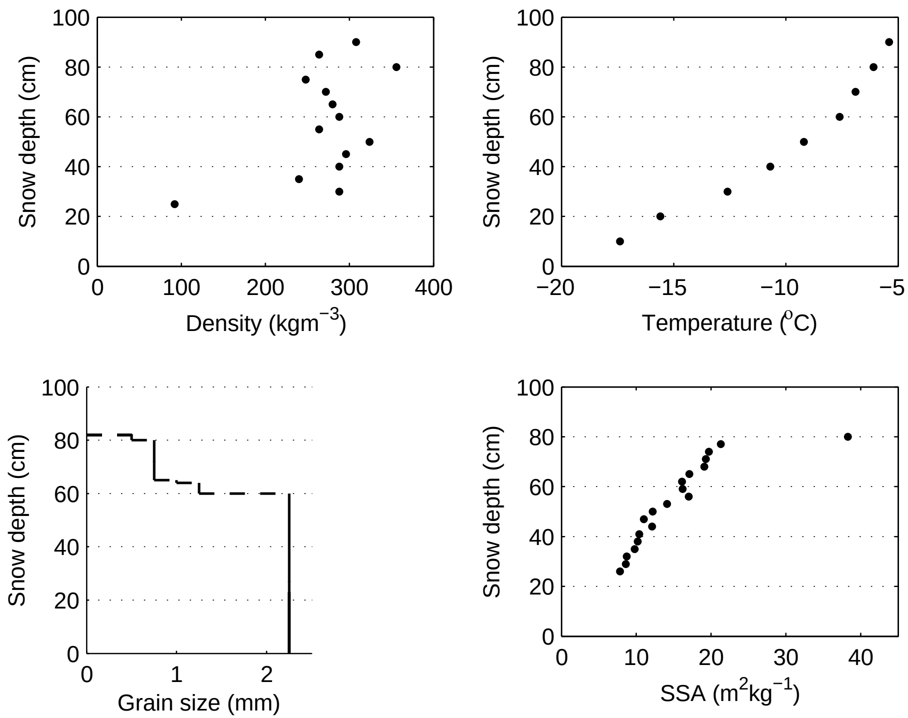

Figure 5. Profiles of density, temperature, grain size (E) and SSA from snow pit 12 March 2013 at IOA. Total SD was 82 cm. One grain size value is estimated from every layer; continuous vertical lines represent grain size over the layer height.

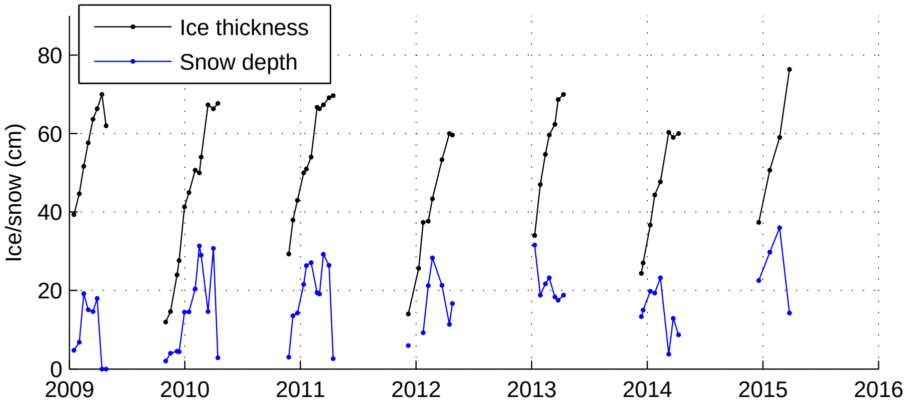

Figure 6. Ice thickness and SD on Lake Orajärvi.