046 KORTRAPPORT / BRIEF REPORT
NORSK POLARINSTITUTT · NORWEGIAN POLAR INSTITUTE 2018

# Protocols and recommendations for the measurement of snow physical properties, and sampling of snow for black carbon, water isotopes, major ions and microorganisms

Editors: J.C. Gallet, M.P. Bjorkman, C. Larose, B. Luks, T. Martma and C. Zdanowicz




Kortrapport / Brief Report no. 046

# Protocols and recommendations for the measurement of snow physical properties, and sampling of snow for black carbon, water isotopes, major ions and microorganisms

Report from two international workshops:
"Taking the next step to the Svalbard snow research" (phase I and II)
Phase I held in Sosnowiec, Poland, September 2015
Phase II held in University of Gothenburg, Sweden, November 2016

Editors: J.C. Gallet, M.P. Bjorkman, C. Larose, B. Luks, T. Martma
and C. Zdanowicz.

The Norwegian Polar Institute is Norway's central governmental institution for management-related research, mapping and environmental monitoring in the Arctic and the Antarctic. The Institute advises Norwegian authorities on matters concerning polar environmental management and is the official environmental management body for Norway's Antarctic territorial claims.
The Institute is a Directorate within the Ministry of Climate and Environment.

*Norsk Polarinstitutt er Norges hovedinstitusjon for kartlegging, miljøovervåking og forvaltningsrettet forskning i Arktis og Antarktis. Instituttet er faglig og strategisk rådgiver i miljøvernsaker i disse områdene og har forvaltningsmyndighet i norsk del av Antarktis. Instituttet er et direktorat under Klima- og miljødepartementet.*

*Addresses:*
Jean-Charles Gallet, Norwegian Polar Institute, Tromsø, Norway, gallet@npolar.no
Mats P. Björkman, University of Gothenburg, Gothenburg, Sweden, mats.bjorkman@gu.se
Catherine Larose, Université de Lyon, Lyon, France, catherine.larose@ec-lyon.fr
Bartlomiej Luks, Institute of Geophysics, Polish Academy of Sciences, Poland, luks@igf.edu.pl
Tõnu Martma, Tallinn University of Technology, Tallinn, Estonia, tonu.martma@ttu.ee
Christian Zdanowicz, Uppsala University, Uppsala, Sweden, christian.zdanowicz@geo.uu.se

The work developed here was supported through SSF/RCN grants 246731/E10 and 257636/E10, Gothenburg Centre of Advanced studies, Biodiversity and Ecosystem services in a Changing Climate, Gothenburg Air and Climate Centre, International Arctic Science Committee - Cryosphere working group, the Center of Polar Studies and KNOW – the Leading National Research Centre and the Norwegian Polar Institute.

The Svalbard Science Forum (SSF) promotes coordination of and collaborative efforts in research activities in Svalbard. This includes managing the "Research in Svalbard" (RiS) database and also supporting organization of workshops targeted towards the polar research community. SSF is administered by the Research Council of Norway.

SVALBARD SCIENCE FORUM

POLISH POLAR CONSORTIUM

The Research Council of Norway


Norwegian Polar Institute, Fram Centre, NO-9296 Tromsø,
www.npolar.no, post@npolar.no

Techincal editors: Gunn Sissel Jaklin, Norwegian Polar Institute
Cover photos: Top left: Sampling snow for physic on Holtedahlfonna, Svalbard (J.-C. Gallet); Middle Top: Snow pit work for physic (T. Martma); Top right: Snow sampling for chemistry and black carbon (B. Luks); Bottom: Kongsvegen glacier, Ny-Ålesund, Svalbard (J.-C. Gallet)
Printed: February 2018
ISBN: 978-82-7666-415-7 (printed edition)
978-82-7666-416-4 (digital edition)
ISSN: 1504-3215 (printed edition)
2464-1308 (digital edition)

*2015 Workshop in Poland, group picture;*
*Back row from left: Alexander Anesio[1], Alexander Prokop[2], Catherine Larose[3], Mats P. Björkman[4], Christian Zdanowicz[5], Jean-Charles Gallet[6], Bartlomiej Luks[7], Daniel Kepski[8], Bock Josue[9], Schiavone Sophie[10], Eric Bernard[10]*
*Front row from left: David Pearce[11], Klaudia Kosek[12], Malgorzata Szopinskap[12], Sara Lehman[12], Katarzyna Kozak[12], Aneta Pacyna[12], Thomas Vikhamar Schuler[13], Krzysztof Migala[14], Elzbieta Majchrowska[15], Elena Barbaro[16], Andrea Spoloar[16]*

[1] University of Bristol, UK; [2] University of natural resources, Austria; [3] Université de Lyon, France; [4] University of Gothenburg, Sweden; [5] Uppsala University, Sweden; [6] Norwegian Polar Institute, Norway; [7] Polish Academy of Sciences, Poland; [8] Centre for Polar Studies, Poland; [9] University of East Anglia, UK; [10] Université de Franche-Comte, France; [11] University of Northumbria, UK/ UNIS, Svalbard, Norway; [12] Gdansk University of Technology, Poland; [13] University of Oslo, Norway; [14] University of Wroclaw, Poland; [15] Polish Polar Consortium-University of Silesia, Poland; [16] University Ca' Foscari of Venice, Italia;

*2016 Workshop in Sweden, group picture;*
*Back row from left: Adam Nawrot[1], Dariusz Ignatiuk[2], Florian Tolle[3], Bartlomiej Luks[4], Catherine Larose[5], Simon Fihol[6], Jack Kohler[7], Christian Zdanowicz[8], Aleksander Uszczyk[2], Zaneta Polkowska[9], Daniel Kepski[10], Christopher Leifsson[11]*
*Front row from left: Andrea Spolaor[12], Krystyna Koziol[1], Elena Barboro[12], Mats Björkman[11], Adrien Boniface[5], Thomas V. Schuler[6], Tõnu Martma[13], J.C. Gallet [7], Aneta Luczkiewicz[9], Linne G. Benning[14], Mariusz Grabiec[2], Elena Marchenko[8]*
*Photo: Jacek Jania[15]*

[1] Institute of Geophysics, Polish Academy of Sciences, Poland; ; [2] University of Silesia, Poland; [3] Université de Franche-Comte, France; [4] Polish Academy of Sciences, Poland; [5] Université de Lyon, France; [6] University of Oslo, Norway; [7] Norwegian Polar Institute, Norway; [8] Uppsala University, Sweden; [9] Gdansk University of Technology, Poland; [10] Department of Polar and Marine Research, Polish Academy of Sciences, Poland; [11] University of Gothenburg, Sweden; [12] University Ca' Foscari of Venice, Italia; [13] institute of Geology, Tallinn University of technology, Estonia; [14] GFZ, German Research Centre for Geo-sciences, Germany; [15] Centre for Polar Studies, University of Silesia, Poland;

# Table of contents

# Introduction

Snow is the only environmental medium that connects the current flagship programmes in Ny-Ålesund (Glaciology, Atmosphere, Terrestrial and Marine Systems). It is at the forefront of climate research, both as an actor and indicator of change. In particular, the critical role of snow in biogeochemical cycles has not been sufficiently investigated. In recent years, the scientific perception of snow has changed from that of an inert or passive medium to a highly dynamic multiphase reactor in which a variety of physical, chemical and biological processes occur.

For decades, the Svalbard archipelago has been an area of interest for chemical, physical and biological investigations of snow and ice, due to its location in terms of climatic interactions and air-mass transport pathways. However, despite the many and demanding field campaigns carried out during the last decades, it has been difficult to link the findings from different projects to obtain a comprehensive picture of snow research conducted in Svalbard. This is in part related to the heterogeneity of field research locations and timing, which hinders direct comparisons between the results of different projects, but also because of the often mono-disciplinary nature of the research being carried out.

In order to address the issue of disparity, the editors of this report established an international network of young and senior scientists with different research backgrounds such as chemistry, biology, physics or other fields related to the cryosphere, that work either directly or indirectly on snow-related research in Svalbard. The inaugural network workshop was financed through a SSG grant in 2014 ("Taking the next step to the Svalbard snow research", ES246731).

Following the establishment of this network, a collaborative pilot project was designed, which successfully obtained a second SSG grant in 2015 (C2S3: "Community Coordinated Svalbard Snow Sampling", ES257636). As part of this proof-of-concept project, the field component of which was carried out in April 2016, we coordinated the work of multiple field research teams in order to perform snow physical observations and collect snow samples across Svalbard for analyses of water isotopes, major ion chemistry, black carbon and microbiological communities using a unified, standardized protocol designed to ensure direct comparability of results. Field observations for the C2S3 project were carried out at seven glacier sites across Svalbard: Austfonna (East), Lomonosovfonna (Central), Hornsund (two glaciers, South West) and Ny-Ålesund (three glaciers, North West).

In November 2016, a follow-up workshop was held in Gothenborg, Sweden, where the first outputs of the C2S3 project were discussed, data shared and continued discussions on sampling and field research strategy issues took place. The present report is based on the last two years of efforts from the snow network, and the outcome of the workshop discussions.

Prior to the field component of C2S3 project, standardized protocols were developed to be used by the different field research teams. By establishing such common protocols we hoped to achieve the following:

1. to ensure that field data were collected in a consistent manner so as to obtain comparable datasets from the different research sites.
2. to ensure that project participants used the same type of formats when labelling samples, and also when recording and storing their field data, in order to facilitate the subsequent processing and sharing of these data after the completion of the field work.
3. to evaluate the efficacy of our protocols (with slight variants) so as to be able to communicate them, through a publication, to a broader audience and thus enlarge our community of snow researchers. The present report aims to fulfil this third and final goal.

**About the C2S3 protocols**

The protocols presented here were designed to focus on specific properties of Svalbard snow packs, namely their physical characteristics (snow texture, density, etc), ionic chemistry, water isotopes ($\delta^{18}O$ and $\delta^{2}H$), black carbon (BC) content and microbiological communities (hereafter: microorganisms). The protocols were designed for the seasonal snow pack on glaciers, in order to exclude the complexity of soil-snow interactions and focus instead on snow - atmosphere interactions. The participating groups in the C2S3 project already had planned field activities on the targeted glaciers, which helped to simplify logistics and reduce field work costs. Furthermore, most targeted sites had been under study for >10 years, and were equipped with Automatic Weather Stations (AWS), from which useful climatological data could be obtained.

One of the main issues to decide upon was what was the best way to sample the snow pack: should we collect snow at constant depth increments, or should we sample snow by discrete stratigraphic layers? This is an ongoing and open debate, and we refer the reader to section 5 of this report for the various arguments. For the C2S3 project, we adopted the strategy to sample discrete snow layers separately, and the protocols that follow were designed accordingly.

This work focuses on glaciers, but it can be adapted to ice caps, once the accumulation is considered so the vertical and horizontal sampling scale might be refined. The same is the case for terrestrial type surfaces, as long as one takes care of the soil interaction, especially for the chemistry and impurity content. These protocols can also be used for sampling on sea ice, but the snow - ice transition can be troublesome, especially when flooding has occurred, which can bring large amounts of salt that completely may saturate the instruments measuring chemistry. Refining the presented protocols to the time and the scale of any study is fairly easy, one simply has to adapt it and take into account the environment in question and the potential artefacts or specificities. The following sections present the protocols, the strategy and the sampling tools we used.

# 1. Beforehand: Preparing a snow pit

## 1.1. General recommendations

Three pits on the glaciers should be dug in early spring (prior to the onset of surface snow melt): one in the ablation zone, one near the equilibrium line, and one in the accumulation zone. If there is one or more Automated Weather Station(s) (AWS) on the glacier, at least one of the snow pits should be excavated nearby, so that the snow stratigraphy can be correlated to AWS recordings.

The snow pit(s) should be dug near the AWS and preferably at the same altitude, but not too close (keep a ~100 m distance to the AWS to avoid any possible contamination or wind drifting effects). Likewise, for any glacier sites accessed by snowmodile, avoid excavating the snow pits near the 'traffic zone' to minimize risks of contamination. On glaciers, this often means the central flow line of the glacier. The sampling should be done upwind from the snowmobile tracks by a few tens/hundred meters (watch for crevasses).

## 1.2. Information to record at each site (metadata)

- GPS coordinates, including altitude (**write down the geoid reference of your GPS**, example: NAD83, WGS84)
- **Take a panoramic photo of the site** (especially important to determine possible local influences, such as proximity of bare ground, for example).
- Date, and local time **at the beginning and at the end** of the snow pit observations.
- **Surface meteorological conditions**: Air temperature, sky conditions (clear sky? partially or totally overcast?), wind speed and direction if possible (as a minimum provide a quantitative indication, such as: strong wind, breeze, calm, etc.), precipitation and phase (if any), presence of fog, diamond dust, surface rime.
- Estimated distance to topographic obstacles, bare ground, nunataks, open water, or **anything that you judge could affect the snow pack conditions**.

## 1.3. Digging the snow pit

- It is critical to **excavate the snow pit properly**, otherwise the quality of the samples taken will be compromised.
- The snow extracted from the pit should be disposed at a good distance on the **downwind side**, to avoid having it slump or drift back into the pit.
- Dig the pit **large enough** so that you can conduct your sampling comfortably, and without touching or hitting the snow wall accidentally.

- On windy days, you may want to place snow blocks on the surface, 1 m upwind of the snow pit, to deflect drifting snow from the snow pit. **Avoid trampling the snow surface between those blocks and the snow pit itself**.

- The face of the snow pit to be examined and/or sampled should be on the **sun-shaded side**, so when digging, take into account the sun's movement across the sky during your work.
- The snow pit should optimally extend **down to the snow - firn - ice transition**. If the pit is deeper than 1.5 m, you might need to create stairs on one side of the pit to come in and out (as far possible to the sampling side, see **Fig. 1**).

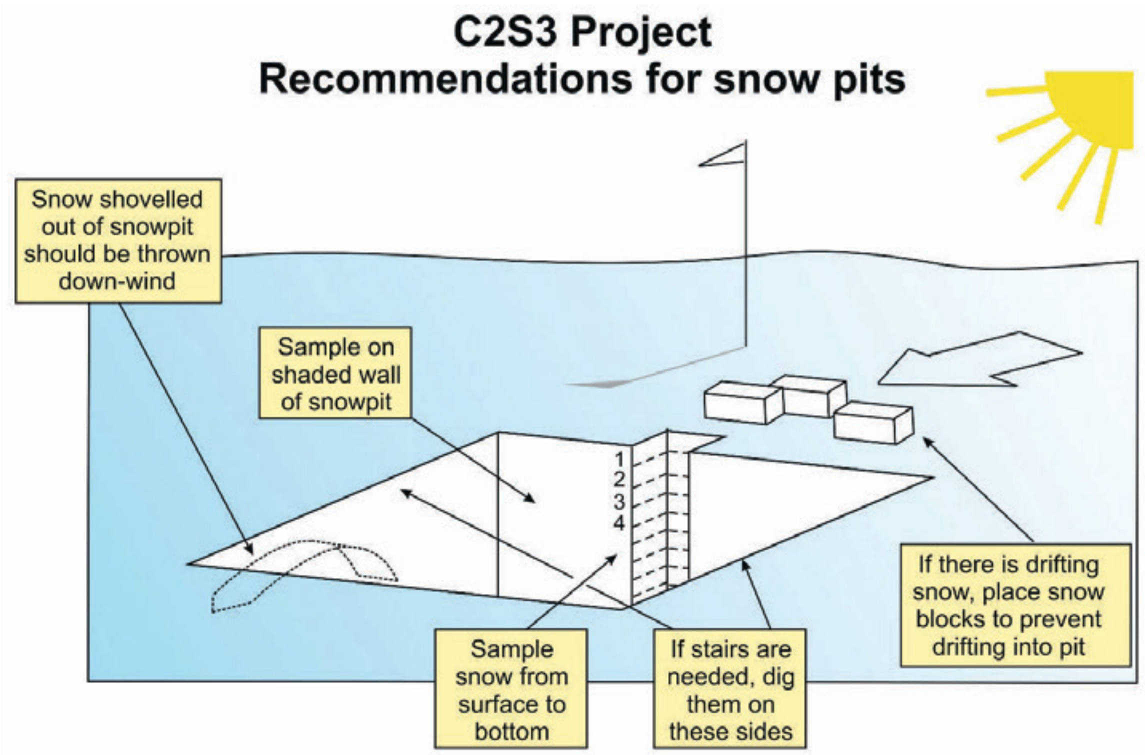



**Fig 1**: Recommendations on excavating snow pits for stratigraphic observations and snow sampling.

# 2. Recording physical and stratigraphic snow data

## 2.1. Recording temperature profile

**The temperature profile should be measured first,** since once the snow pit is dug, the walls will either cool down or warm up. Start at the air/snow interface and take temperature measurements every 5 cm near the surface (0 to 20 cm depths), and then in each discrete layer, with at least one measurement for every 10-cm depth increment. The last measurement should be at the bottom (snow/firn or snow/ice or interface)

## 2.2. Recording snow stratigraphy

- Put a ruler on the face of the pit to record the depth of the measurements and stratigraphy, the **0 cm level being at the top of the snow pit (0 = surface).**
- Begin by examining the snow pit wall, and **record the stratigraphic sequence and thickness of each distinct layer** (position and thickness). You can use a brush (soft painting brush type) to gently swipe the surface of one part of your snow wall, as it might help you to distinguish the layers.
- **As a visual reference, you can insert colored markers** (such as plastic knitting needles) at the interface of the different layers in the snow wall, provided that you do not subsequently take snow samples where these makers were inserted. Markers can be helpful if the light conditions are poor (example: overcast) as it is difficult to visually identify the interfaces between layers.
- The following snow descriptors have to be recorded for **each layer**:

**Texture: Snow grain shape.** Use magnifying glass in tool kit.
Refer to appendix: snow crystal identification guide.

**Texture: Snow grain size.** Use the graduated scale card provided in the kit.
**Record the actual min and max grain size (mm) you observe.**

| Term | Size (mm) |
|---|---|
| Very fine | < 0.2 |
| Fine | 0.2–0.5 |
| Medium | 0.5–1.0 |
| Coarse | 1.0–2.0 |
| Very coarse | 2.0–5.0 |
| Extreme | >5.0 |

**Table 2.1.** Recommended grain size scale from Fierz *et al.* (2009; Table 1.3)

**Hardness.** Use the 'hand test' (see below). If you have access to more precise tools (e.g., a rammsonde or penetrometer), you can use them, but **report the hand test results as well, for comparability**. Note that the hardness measurements can guide the optimal strategy for density measurements.

| Term | Hand hardness test | | | Ram[2] test (N) | | Symbol |
|---|---|---|---|---|---|---|
| | Index | Object | Code | Range | Mean | |
| Very soft | 1 | Fist | F | 0-50 | 20 | / |
| Soft | 2 | 4 fingers | 4F | 50-175 | 100 | X |
| Medium | 3 | 1 finger | 1F | 175-390 | 250 | // |
| Hard | 4 | Pencil[1] | P | 390-715 | 500 | XX |
| Very hard | 5 | Knife blade | K | 715-1200 | 1000 | ■ |
| Ice | 6 | Ice | I | >1200 | >1200 | |

*[1]Here, 'pencil' means the tip of a sharpened pencil. [2]Swiss rammsonde.*

**Table 2.2.** Recommended hardness scale from Fierz *et al.* (2009; Table 1.4)

## 2.3. Measuring snow density

Density must be measured in each stratigraphically distinct layer, unless a layer is too thin, or discontinuous, or too hard or loose to be sampled. Use the sampling tools provided, which include a 100 $cm^3$ cutter. **Begin by weighing the dry, empty cutter on the scale, and record its weight**.

**If there are large disparities in the snow density** within the same layer (for example: dense and compact at the top, loose and crumbly at the bottom), **take separate measurements**, recording the depth of each. Weight the samples **within the cutter** on the scale. The density is calculated by dividing the net weight of the sample (after subtracting the weight of the empty cutter) by the cutter volume.

**If you encounter a thick snow layer** (e.g., 20 cm), take several measurements (top/middle/bottom of the layer) at different positions in the layer.

**If you encounter a very compact/icy layer** that your density cutter can not penetrate, you can cut a small block from the layer using a snow saw, measure its dimensions (height, width, length), and weight it to obtain a density estimate.

## 2.4. Snow pack density for snow water equivalent

In order to optimize measurements for different disciplines, it is suggested to measure the density of the whole snow pack (i.e, **vertically**). These measurements provide an estimate of the full mass load of accumulated snow, which is required to calculate the surface mass balance of glaciers, and is complementary to the above discrete layer measurements since it integrates all snow strata.

Method: Insert a cylindrical snow cutter (in this example: 20 cm long) vertically from the snow pack surface down to 20 cm depth using a spatula inserted in the snow pit wall as a stopper. Pour the snow from the tube into a plastic bag and weight it on the scale. The density can then be calculated since the volume of the tube is known. Repeat the process for depth intervals 20-40 cm, 40-60 cm, and so on until the bottom of the snow pit.

## 2.5. Snow kits provided for the C2S3 project

For the C2S3 project, snow tool kits were provided to ensure that each participating group used the same tools for describing snow pits. Each kit was packed in a rugged Pelican case so it could easily be transported and attached on a snowmobile sledge. The contents of each kit was:

- 8X magnifying glass and graduated plate to observe snow crystals
- Digital thermometer to measure snow temperature
- Snow cutters with 100 $cm^3$ capacity to measure snow density
- Digital weighing scale with a maximum load of 2000 g and a precision of ± 1 g
- Folding rulers (1 and 2 m, plastic) to record snow depth
- Several plastic and one stainless steel spatula(s)
- Two brushes

<u>The following recommendations were given to each groups:</u>

“ Bring **several sturdy shovels**, so that several people can participate in digging snow pits, and as spares. It is also recommended to use an extra strong shovel (e.g., steel) if in an area that experiences winter melt or rainfall events (like Svalbard), as plastic and aluminium shovels often break on ice layers. For deep digging, a short shovel is recommended, easy to handle in a limited and confined space as a snow pit is. Using a saw can also be helpful for very hard layers to saw small compact blocks and excavate the snow that way.

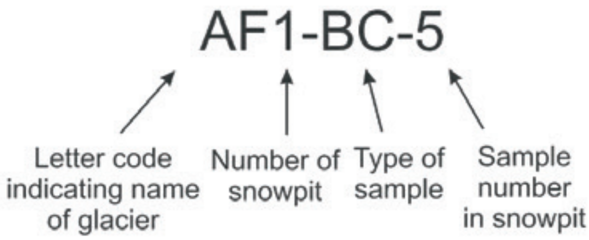
**Reference cited:**

Fierz, C., R. L. Armstrong, Y. Durand, P. Etchevers, E. Greene, D. M. McClung, K. Nishimura, P. Satyawali, and S. A. Sokratov (2009), *The International Classification for Seasonal Snow on the Ground*, IHP-VII Technical Documents in Hydrology N°83, IACS Contribution N°1, UNESCO-IHP, Paris.
Downloadable at: http://unesdoc.unesco.org/images/0018/001864/186462e.pdf

## 3. Sampling snow for water isotopes and impurities*
### (*BC, major ions and microorganisms)

### 3.1. Labeling samples

During the C2S3 project, we adopted a standardized labeling convention for all snow samples to ensure a maximum of coherence and avoid confusions in the subsequent processing of samples with various laboratories. This is illustrated by the example below.




**The first set of characters identified the field site and the snow pit**. In the example above, AF1 indicated that the sample was taken at the first snowpit (1) on Austfonna (AF). Of course the geographic coordinates of each snow pit were recorded in field notes.

**The middle set of characters indicated the purpose for which the sample was collected**. A simple letter code was used, where ISO = water isotopes, ION = major ion chemistry, BC = black carbon, and M = microorganisms.

**The number at the end of the character string identified the sample position in the sampling sequence**, sample # 1 being to closest to the surface. The exact depth interval of each sample was recorded in field notes, and could also be added on the label to provide extra information.

This labelling convention could easily be adapted to other settings.

### 3.2. Sampling for water isotopes ($\delta^{18}O$ and $\delta^{2}H$)

**General recommendations**

The recommended procedure for sampling for both water isotopes and major ions is shown in **Fig. 2** below. Sampling should be done along the snow pit wall down to the desired depth (e.g. until the bottom of the seasonal snow pack). Contamination during sampling is not a major concern, so you can take these samples whenever you wish **but make a fresh face on the pit wall beforehand! It is also recommended to sample after the snow stratigraphy has been examined and described in order to have a better identification of the different snow layers.**

Once discrete layers have been identified, samples for water isotopes can be taken at every 5 cm (maximum) within each individual layer, or at shorter depth intervals if the layers are < 5 cm thick. For example, a 7 cm layer will consist of two samples, one for the top 3.5 cm and a second for the lower 3.5 cm.

**Once a sample is collected, you should immediately label the vial.**

The volume of water required for $\delta^{18}O$ and $\delta^{2}H$ measurements is 15 mL, but larger sample volumes are recommended to allow for duplicates. Snow samples are to be taken in wide-mouth polypropylene or high-density polyethylene (HDPE) vials. Plastic bags are not recommended.

Water isotope measurements are not sensitive to contamination by particulate impurities like BC or micro - organisms. However, sublimation after sampling and/or evaporation during melting or during storage of liquid samples can modify their original ratios of oxygen and hydrogen stable isotopes. **Therefore, always ensure that the sampling vials are correctly sealed.** Small ice crystals can sometimes get wedged between the bottle neck and cap, or in the cap thread, preventing correct closure of the vials.

Once back at a field station, you can either keep the samples frozen or melt them, depending on your options for shipping to the laboratory where the analyses are to be performed. **We recommend to ship samples in liquid state**, as sending frozen goods is both risky and expensive, but depending on the type of analyses, some of them require the samples to be kept frozen. Regardless of how they are shipped, **make sure that the vials are tightly closed and the labels on them are readable.**

If you decide to melt the samples prior to shipping, make sure the vials from the field are correctly closed and let them at room temperature for melting slowly. Once melted (do not forget them, otherwise they will evaporate), you should transfer the melted snow in HDPE Nalgene bottles. Nalgene bottles are very robust and have really good caps that ensure there won't be any evaporation, if correctly sealed. Store bottles at +4 °C until shipping to the lab. A few weeks storage at +4 °C is not a problem but for longer storage time, -20 °C storage is required. You should then refreeze the water collected from melted snow samples, but this operation can damage the bottles due to water expansion when changing phase, so be careful to not fill the Nalgene bottle too much if you have to do that operation. **However, remember that if left stored in liquid form over months, water vapour can diffuse through HPDE bottle walls.**

## 3.3. Sampling for major ions

Make sure all layers are well marked in your snow stratigraphy description. Use a ruler to record the samples depth. For major ion analysis, the minimum volume of water needed from each layer is ~25 mL, or ~50-75 mL of snow. Samples can be collected in wide-mouth cylindrical vials or bottles made of polypropylene or HDPE, **as long as the chosen containers have been tested for acceptably low blank values beforehand**.

After the snow pit is established, dress up in clean suits, gloves, face mask, etc. **All the sampling equipment (suits, bags, scraps etc.) must be kept sealed in plastic bags until they are ready to be used, in order to avoid contamination. Make a new clean face by removing the outer 10-20 cm** from the sampling face of the snow pit using a clean plastic tool. Before sampling, carefully 'rinse off' all the tools in the snow to be used by pushing them in and out of a clean part of the snow pit wall several times. Start from the surface layer and carefully move snow (or ice) from each layer into the sampling bags.

**Each individual layer should be sampled** in such as way that a representation of the whole layer is obtained. Hence, if a layer is thick, this may require taking two or more separate consecutive samples.

For each snow pit, and in addition to samples, **three field blanks should be obtained before or after sampling.** Open the bags/vials for these blanks, and keep them open and exposed to outside air for a minute, then close the bags without any addition of snow. Clearly identify the bags/vials as field blanks, and indicate at which snow pit site they were taken. During analysis, these bags will be filled with 100 mL of ultra-pure water and serve as a blank control to quantify any contamination introduced during sampling and/or transport.

**Sampling tools provided for the C2S3 project:**

- Clean plastic shovels, scrapes and scoops
- Clean suite, gloves and facial mask
- Knitting needles with different colors
- Measuring tape
- Sampling vials, polypropylene or HDPE 50, mL
- Marker pens

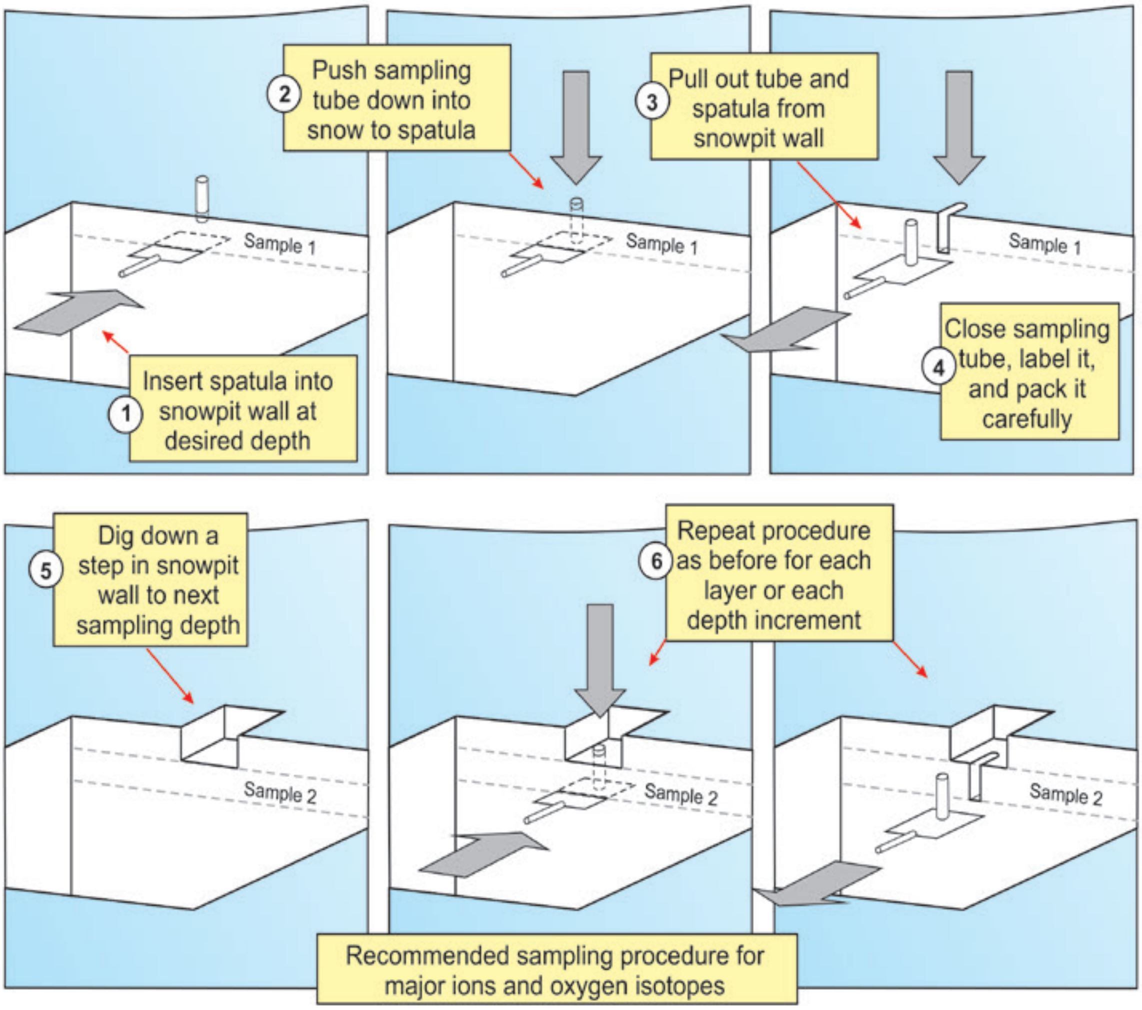



**Fig. 2.** Recommended sampling procedure for major ions using cylindrical vials.

## 3.4. Sampling for BC and microorganisms

BC is usually present in very small amounts in polar snow, and the risk of contaminating samples is high if appropriate precautions are not taken. **Possible sources of contamination are scooter exhaust, cigarette smoke and clothes that can catch particles.** Therefore, when travelling by snowmobiles, or when sampling in areas where people have been driving snow scooters, **move away from the traffic path** (often the central line on a glacier), and park and turn off your snowmobile **at least 50 m downwind of the sampling site** (i.e. walk at least 50 m upwind).

**Do not sample BC while wearing your snowmobile suit and gloves. Cover your clothes with extra-large non-particulating coverall suit and disposable plastic gloves (provided with the tools for C2S3). Pull the hood of the coverall suit on your head and over your hat.**

All precautions for BC outlined above also apply when sampling for microorganisms.

**Sampling tools provided for the C2S3 project:**

- Sterile bags, disposable gloves and face masks
- Sterilized sampling tools: Teflon or stainless steeled.
  (Rinse metal tools with ethanol between each snow layer sampled)

The sampling protocols for BC and microorganisms are very similar, and both types of samples are to be collected in 5.4 L Whirl-Pack bags, provided with the sample kits. An essential difference is the volume of snow needed:

**For BC:** ~10 L of snow per sample. This means 2-3 full bags by sample.
**For micro - organisms:** 2-3 L of snow per sample. This means 1 bag by sample.

The sampling protocol, **for both BC and micro - organisms**:

- A sample **from the top 5 cm of the snow pack only**. The BC in the uppermost layers has the largest impact on snow albedo, so it must be quantified separately.

- The next sample goes from 5 cm below the surface, down to the interface between snow layers that is nearest 50 cm depth. It may happen that there is, for example, a thick, continuous snow layer between 35 and 60 cm depth. In such a case, take the sample down to 60 cm depth. In all cases, **record and write down the exact depth range of the sample on the bag using water proof pens. Under cold conditions, the ink can take a while to dry, so you can easily erase it accidentally, loose your labelling information and get some on your gloves/suit handle that could contaminate following samples.**

- Continue sampling at approximate 50-cm depth increments down to the bottom of the snow pit. If the lowermost sample is < 10 cm thick, combine it with the one above it (and make sure to record this in your notes and on the bag). For example, in a 166 cm deep snow pit, you might get: Sample 1: 0-5 cm; Sample 2: 5-52 cm; Sample 3: 52-108 cm; Sample 4:108-166 cm

- **All samples should have approximately the same volume** (~10 L each for BC and ~2-3 L for micro - organisms)

- A suggested method for sampling (**Fig. 3,** below) is to cut wide snow blocks with a saw (clean the saw first). Adjust the width and length of the blocks to obtain the desired volume of snow. You can cut steps and blocks, working your way down the snow pit wall, until you reach the bottom.

- **Remember that the whole depth-interval of each sample must be sampled.** So do not fill up a bag with only the top 35 cm of a 50-cm depth interval: collect snow from all depths in this interval.

- You should also sample the same surface area for each layer (continuous column with the same length and width, the depth depend on your chosen increment/resolution). Do not sample huge blocks at the top and small blocks below because the bag is full, otherwise you oversample the upper part compare to the lower part. Adjust the column surface area to the volume you need.

- Close the Whirl-Pack bags carefully. The top of the bags is closed by folding the lip onto itself several times, and then twisting the yellow wire tabs together. Double-bag the samples for greater safety is recommended.

- **Carefully and clearly write the sample ID and the depth intervals on the bags** with a waterproof marker.

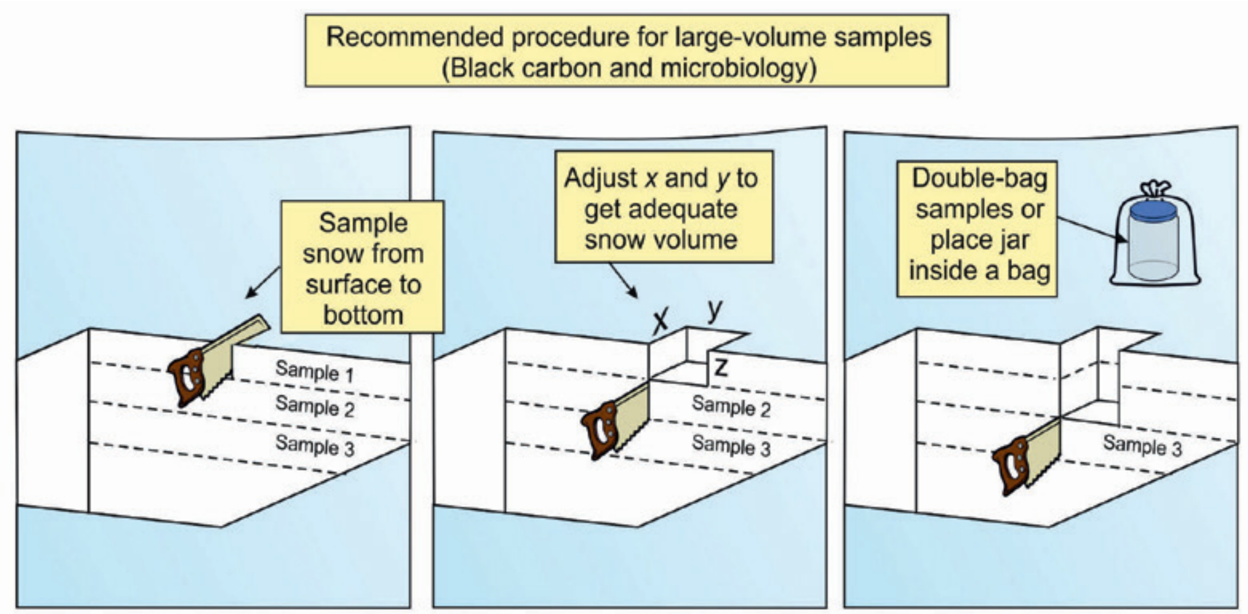



**Fig. 3:** Recommended procedure for large-volume samples.

**Note for the 5 cm top surface sample:** Place a ruler as shown on **Fig. 4** (below) to guide your sampling. Fill the bags or jars with the plastic spatula. Sampling the top snow surface can be challenging as you might need to cover a large surface to fill in the jars or bags in order to get the amount of melted water required for your measurement method.

It is crucial to keep a large area of clean and untouched snow in order to collect the amount of snow needed as close as the other samples taken further down. **Protect your sampling area!**

**Fig. 4:** Sampling surface snow using spatula and ruler (Picture C.A. Pedersen)

Based on previous experience, the melt water volume needed to measure BC in Svalbard snow by the thermo-optical method is ~2-3 L. How much snow this requires you to sample will be dependent on the snow density. For fresh and light snow, collect 10 L. If the snow is denser or old (melt refreeze crust), 5 L might be enough. To reduce the number of bags and jars used, you compact the snow in the jars or bags by shaking them.

**After sampling, all samples should be kept frozen until processed for analysis.** If the analytical technique requires the snow to be melted and filtered afterwards, it is recommended that this procedure be undertaken as soon as possible after collecting the samples.

## 4. Diagrams: Snowpit sampling strategies

The diagrams on **Figs. 5-7** below present examples of the recommended snowpit sampling strategies for the C2S3 project.

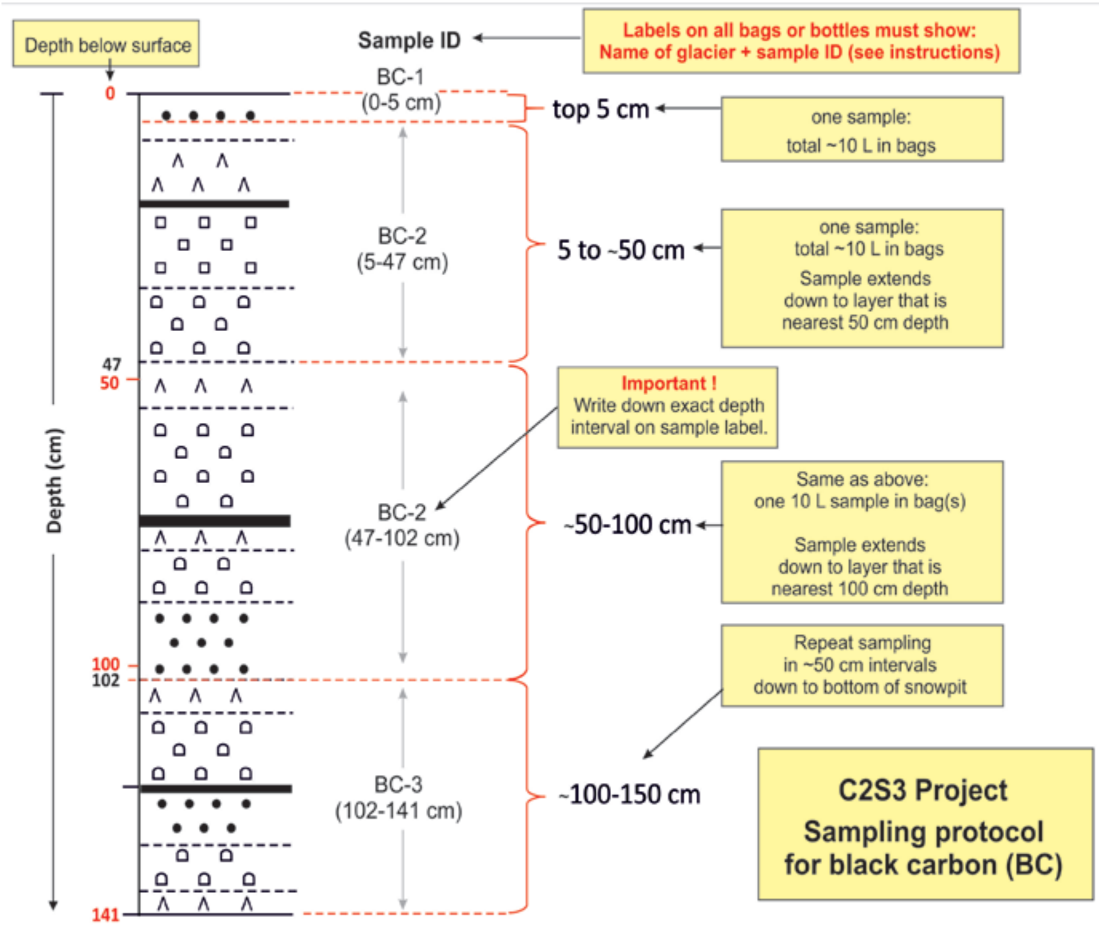



**Fig. 5:** Sampling strategy for black carbon.

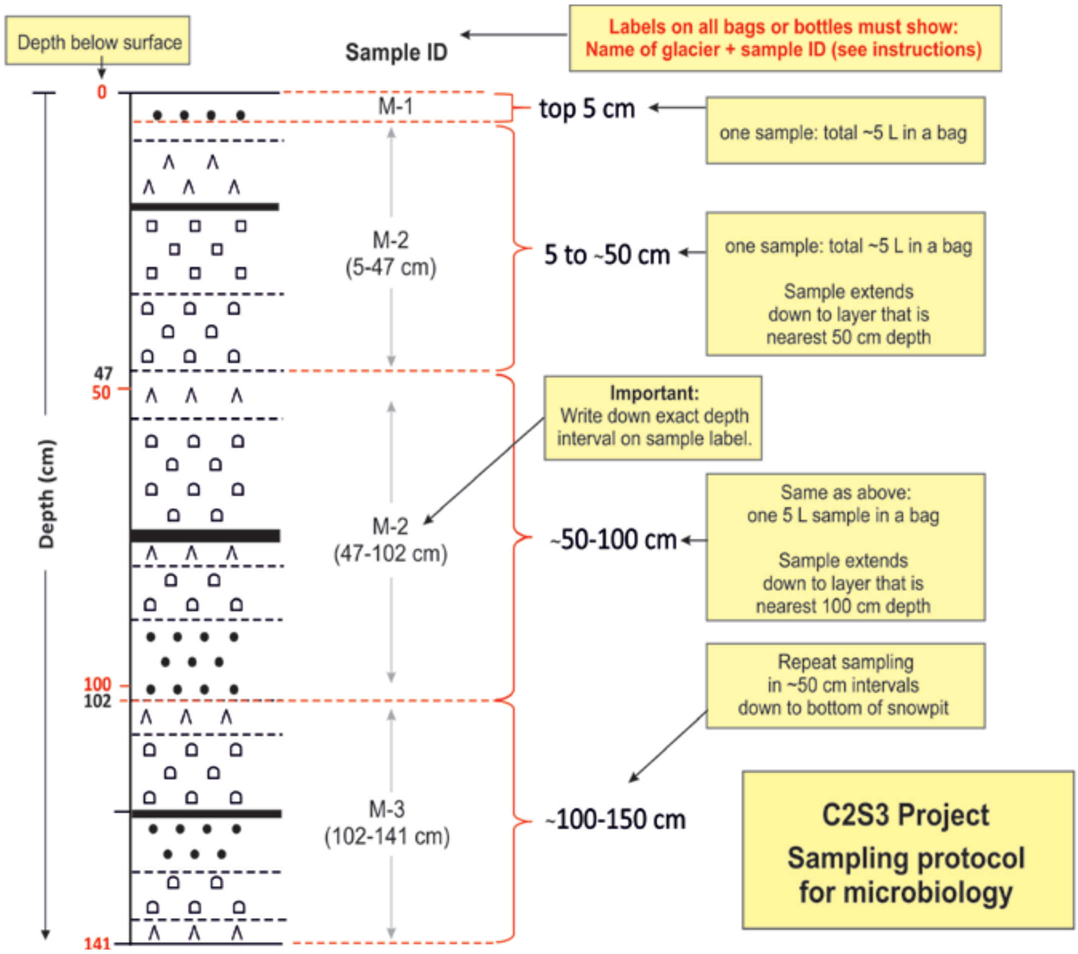



**Fig. 6:** Sampling strategy for microorganisms.

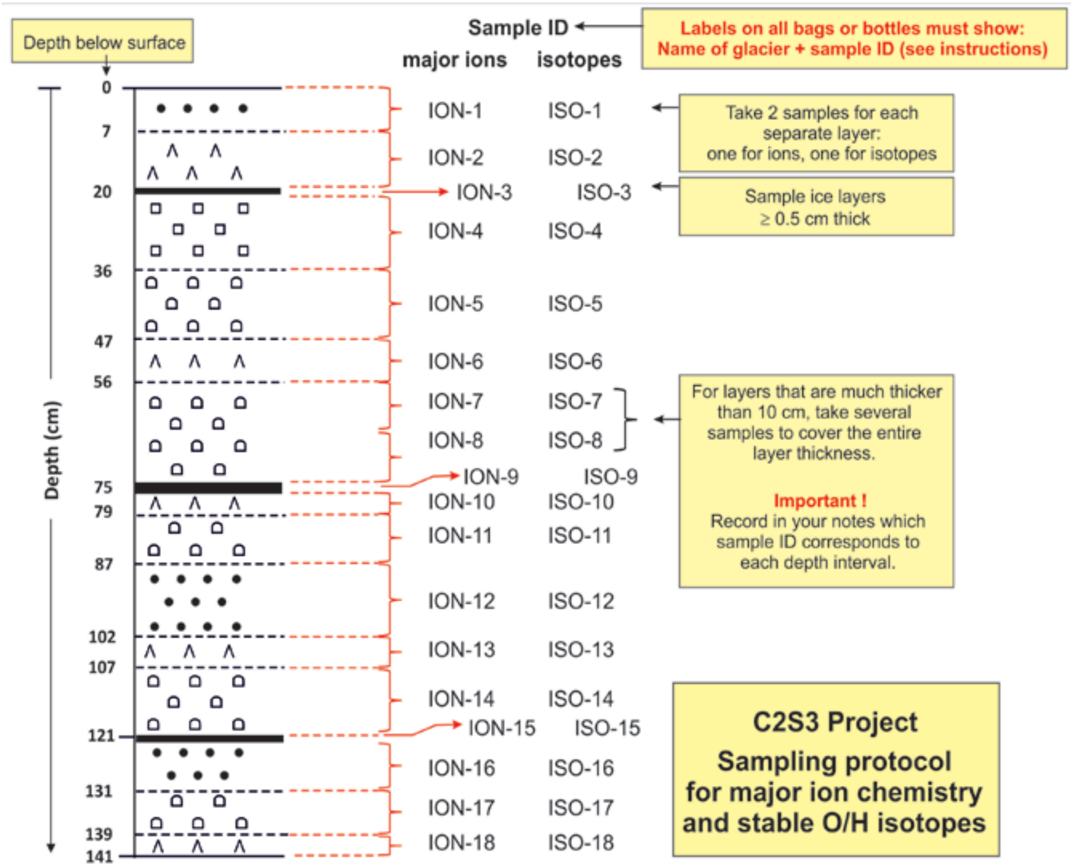



**Fig. 7:** Sampling strategy for water isotopes and major ions.

## 5. Discussion: What is the best snow sampling strategy ?

In this section we summarize the respective advantages of sampling the snow pack either by discrete snow layer, or using fixed depth increments. Our choice for the C2S3 project was to sample per discrete snow layer, in the following we explain why.

**Sampling per discrete snow layer** offers the potential benefit to be able to link a snow layer (and its properties) to a specific climate event, such as a period of precipitation or surface melt, provided of course that an independent record of such events can be obtained, for example from a AWS data-logger. When investigating the ionic chemical composition of snow or its BC content, as we did, this is of particular interest as it may help identify the atmospheric sources of impurities deposited in the snow pack by tracking the origin of air associated with specific snow accumulation periods. Sampling by discrete layer also makes it possible to correlate intervals of snow accumulation between separate snow pits at different altitudes, for example on a glacier between its ablation and accumulation area, which was relevant in the C2S3 project. The snow pack stratigraphy may vary over an altitude range with the precipitation amount and phase (rain vs. snow), such that the same precipitation event might be represented by an ice layer in the lower reaches of a glacier and by a snow layer in its upper part. Hence, sampling per discrete layer allows to connect and compare snow pack properties in different parts of the same glacier. Finally, if repeat sampling is planned at a given site, sampling by discrete layer allows to track how surface melting modify the physical properties of the snow.

**Sampling by fixed depth increments** has the advantage of being the simplest and easiest protocol to use by multiple teams in the field, since it does not require a description of the snow pack stratigraphy to be made *a priori*. Secondly, for certain types of studies, it is of interest to know exactly how snow pack properties vary as a function of depth, and in such instances, a fixed depth-interval strategy works best for comparing results from multiple snow pits. Temporal variations can also be compared but without accounting for precipitation events. Sampling per fixed depth increments is particularly useful when studying the radiative properties of snow and photochemical processes in the snow pack. It is also useful for quantifying the deposition of atmospheric species at the snow surface if snow - atmosphere interaction is the main focus.

Both strategies have advantages and inconveniences, and the choice of the most appropriate one must be guided by one's research objectives and needs. Here, as our interest is to follow the deposition of aerosols and their links, the origins of these aerosols are important for us, so the air mass. Therefore, the sampling during the C2S3 project was done per discrete layer.

## Conclusions

In this document we have presented the detailed snow sampling protocols we designed and applied to a pilot study in Svalbard in the C2S3 project. We hope to provide the basis for future interdisciplinary research, and that these protocols will increase the results quality, particularly when dealing with multiple research fields and questions. We also wanted to share these protocols so that people with less experience working on snow, directly or indirectly could benefit from them. By following this protocol, one should be able to collect data in a consistent manner and share and store the data on a common platform, thus facilitating the intercomparison of snow data, the validation of models and reducing the cost in collecting data, both in terms of economic and human resources.

The work described here is simply an attempt by our group to show that by using such a strategy, it is possible to collect a large amount of samples with a minimum of effort and in a consistent manner. This work should not be taken as a “what should be done” but more as an example of “what could be done”. Any advice and recommendations are very welcome, do not hesitate to contact us.

## Acknowledgements

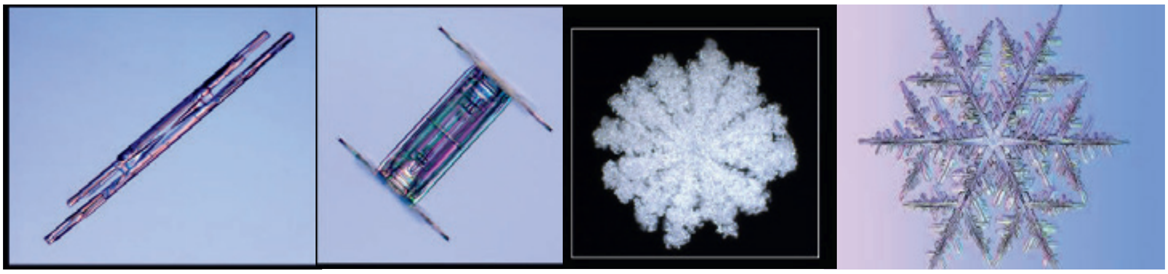
This work consist on direct outputs from two different workshops held in 2015 and 2016, supported by the Research Council of Norway (Svalbard Strategic Grant), Gothenborg Centre of Advanced studies (GoCAS), Biodiversity and Ecosystem services in a Changing Climate (BECC), Gothenborg Air and Climate Centre (GAC), International Arctic Science Committee: Cryosphere working group, Center of Polar Studies and KNOW: the Leading National Research Center. We acknowledge their financial support as well as the local hosts for organizing the workshops: University of Silesia, Poland, and University of Gothenborg, Sweden. The pilot study C2S3 for which we tested the protocols was supported by the Research Council of Norway (Svalbard Strategic Grant), and we also acknowledge their support. We acknowledge the huge contribution from all partners, without whom the field sampling would not have been possible (Hornsund field team with the deepest almost 4 meter snow pit; Ny-Ålesund snow diggers; University of Oslo and Norwegian Polar Institute for Austfonna samples, University of Uppsala for Lomonosovfonna samples).

We are also very grateful to our partners and colleagues that provided us feedbacks and inputs when designing the protocols and the pilot studies. We also acknowledge the help, support and encouragement from our senior collaborators that always provided us with great inputs and pushed us to go forward in the work we developed so far.

## APPENDIX: SNOW CRYSTALS IDENTIFICATION GUIDE
**(written for Svalbard snow and limited to the most common snow crystals)**

The most common snow textures and snow grain shapes in Svalbard are: **(1)** Fresh/precipitating snow; **(2)** Fragmented snow; **(3)** Windpack; **(4)** Faceted grains; **(5)** Rounded grains; **(6)** Depth hoar; **(7)** Melted forms; **(8)** Melt refreeze crust; **(9)** Ice lens; **(10)** Ice layers. **These 10 types should be recognizable quite easily**.

**(1)** Fresh and precipitating snow can be: From left to right: column, cupped plate (or simple plate), rimed snow and dendritic crystals. *Pictures: "SnowCrystals.com"*



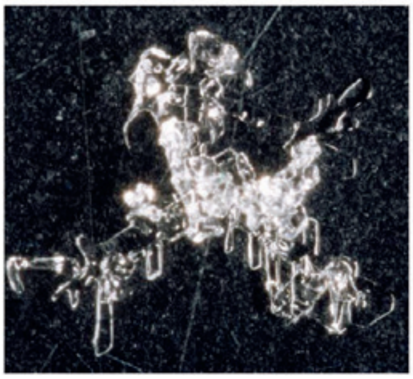
On the next page more pictures are shown, **with a 1 mm white scale bar** on each.
**(2)** is made of broken parts of still recognizable fresh snowflakes (broken dendrites on the picture), usually observed at the surface under windy conditions after a fresh snowfall.
**(3)** is often in a hard layer, and it can be difficult to get crystals out without breaking the bonds, sometimes formed under strong wind conditions.
**(4)** is very distinctive and very common in Svalbard, the facets are very visible with sharp edges.
**(5)** is often due to slow metamorphism or to remobilization by slight wind, made of fine grain. Can be single or in clustered, often both.
**(6)** is typical depth hoar, often a hollow cup but not always, but the main diagnostic features are the striations, made by steps during crystal growth, typical of strong metamorphism. Often observed at the base of the snow pack.
**(7)** and **(8)** look similar: (7) is still liquid so you will feel it when sampling (snow is sticky, wet). (8) is refrozen, much harder to sample.
**(9)** and **(10)** are ice structures. Ice lenses are often formed by percolation/refreezing of melt water, discontinuous and at most few mm thick. Ice layers are formed by strong melting event or rainfall and often continuous and thick (few mm to cm). These are important markers both for the physics and the chemistry of the snow pack, especially the ice layers since these can often be attributed to a specific climatic event (warm spell, rainfall).

These are only general descriptions, and snow is often made of a mixture of all these grains. Many more structures can be found in the snow pack.

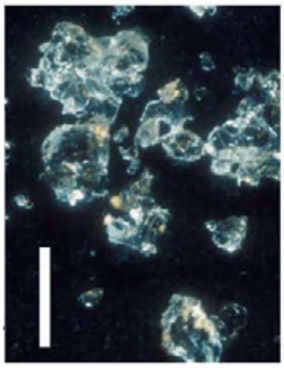
**The most important thing is to at least try to identify if the snow is either:**

**Fresh:** fresh precipitation, strong albedo, soft, low density
**Wind-packed:** after a wind event, harder, high density
**Faceted/depth hoar:** level of metamorphism of the snow (temperature gradient)
**Rounded grain:** low temperature gradient, slow metamorphism
**Melt/refreeze crusts or ice layers/lenses:** Melt, percolation, rainfall event.

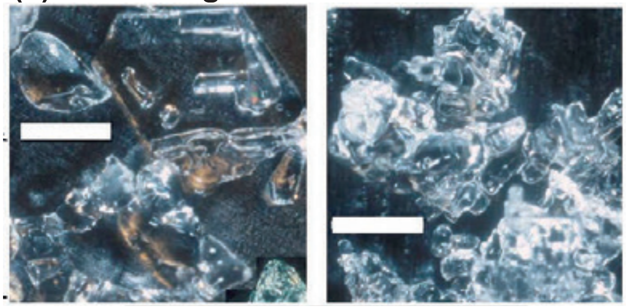
**(2) Fragmented snow**



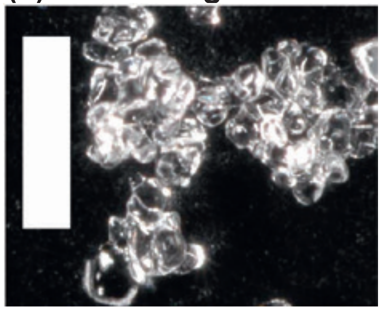
**(3) Wind-packed**



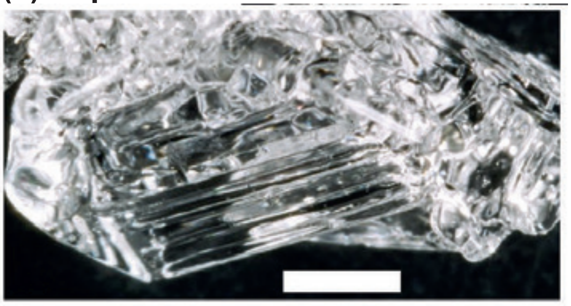
**(4) Facetted grains**



**(5) Rounded grains**

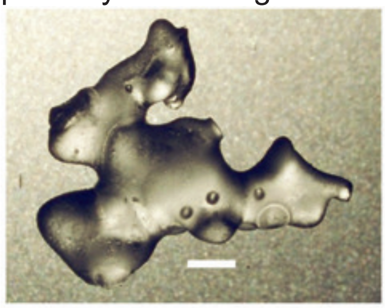


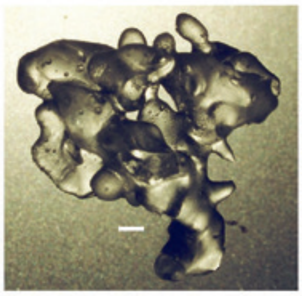
**(6) Depth Hoar**



**(6) Depth hoar**

(**7) Melted forms and (8) Melt-refreeze crust**: often made of large rounded grains, possibly containing some sharp parts, but very hard, difficult to sample.





**(9)** Ice lenses (not shown), made up of at most few mm of ice, in the form of a lens (not laterally continuous)
**(10)** Ice layers (not shown): laterally continuous layer of ice that you can follow along the snow stratigraphy, often made up of few mm and up to several cm

Photos: *F. Dominé and A.S. Taillandier*. **Scale bar is 1 mm on each picture.**

Miljømerket trykksak 2041 0699 | Trykk: Bodoni