A UNIQUE TIME SERIES OF DAILY AND WEEKLY SNOWPACK MEASUREMENTS AT WEISSFLUH-JOCH, DAVOS, SWITZERLAND

N. Calonne[1]*, C. Cetti[1], C. Fierz[1], A. van Herwijnen[1], M. Jaggi[1], H. Löwe[1], M. Matzl, L. Schmid[1] and M. Schneebeli[1]

[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

ABSTRACT: Recently, different efforts were dedicated to improve various components of snowpack models, notably, by including more objective parameters of snow microstructure. To contribute with a dataset for this purpose, we designed a new measurement campaign for the winter 2015-2016 at Weissfluhjoch, Switzerland. We focused on density and specific surface area (SSA) of snow, two fundamental microstructural parameters from which many physical snow properties can be estimated. Weekly measurements of density (density cutter) and SSA (*IceCube*) profiles at 3 cm vertical resolution now extend the traditional snow measurements. To investigate also short time evolutions, daily *SnowMicroPen* measurements were additionally done from which proxies of density and SSA can be calculated at 1 mm vertical resolution. Occasionally, snow samples were also taken from the snow pit for micro-tomography measurements to investigate specific snow cover features, such as weak layers, graupel or crusts at a 10 micrometers resolution. Finally, Propagation Saw Tests were performed nearly on a weekly basis. In this paper, we present an overview of this measurement campaign carried out from December 2015 to March 2016. We show preliminary results of the density profile evolution that highlight the advantage of daily measurements compared to weekly ones when aiming at a highly continuous picture. The present dataset offers new opportunities for calibrating and validating physically based snowpack models, as well as for a better understanding of processes such as fracture propagation, snow densification, or crust formation.

KEYWORDS: density, specific surface area, snowpack, monitoring, measurement.

1. INTRODUCTION

In Europe, three main snow monitoring sites with a long history of regular measurements of snowpack properties exist: Sodankylä in Finland (Essery et al. 2016), Col de Porte in France (Morin et al. 2012) and Weissfluhjoch (WFJ) in Switzerland. While Sodankylä is an Arctic site, Col de Porte and WFJ are located in the Alpine regions. WJF, at an elevation of 2536 m corresponds to a high elevation site, compared to 1325 m for Col de Porte. Among other goals, these “reference” sites have been used to build snowpack models in Europe, such as Crocus (Vionnet et al. 2012) or SNOWPACK (Bartelt and Lehning 2002).

Presently, efforts are underway to improve certain components of snowpack models, and, notably, to incorporate more objective parameters of snow microstructure that can be directly compared to measurements. Among different microstructural parameters, density and specific surface area[1] (SSA) are the fundamental ones from which the majority of the physical snow properties, such as thermal conductivity, dielectric permittivity, or permeability, can be already estimated. Along these lines, the traditional grain size was replaced by the SSA in Crocus (Morin et al. 2013, Carmagnola et al. 2014).

To provide a dataset needed for the validation of new model components, we started to include measurements of additional parameters in the regular observation program at the WFJ site. Weekly measurements of vertical profiles of density and SSA now extend the traditional snow profile.

Only little data exist on the short-time scale evolution of the snow cover. At best, weekly snow pit measurements were performed at the three sites cited above. However, processes such as crust formation, layer compaction, development of sur-

* *Corresponding author address:*
N. Calonne, WSL Institute for Snow and Avalanche Research SLF,
Flüelastrasse 11, 7260 Davos Dorf, Switzerland;
email: neige.calonne@slf.ch

[1] The SSA is the ratio between the surface of the ice grains over the volume of the ice grains contained in the considered snow volume. The SSA can be used to estimate the average size of the ice grains.

face hoar, or faceting can occur over much shorter time scales than one week (e.g. Stössel et al. 2010, Pinzer et al. 2012). Thus, we started a novel attempt that aims at monitoring the evolution of density and SSA on a daily basis. To this end, we chose the penetrometer *SnowMicroPen* (SMP) (Schneebeli et al. 1999) to benefit from rapid measurements and that can be combined with the method of Proksch et al. (2015) to obtain estimates for density and SSA.

In this paper, we present an overview of the measurement campaign at WFJ during the winter 2015-2016. We focused on the time from December to March where the snowpack was mostly dry. The campaign was primarily designed to provide a time series of density and SSA at different spatial and temporal resolutions. While a detailed evaluation of the data is currently in progress, we present in the following preliminary results of snow density.

2. MEASUREMENT CAMPAIGN

2.1 *Instruments*

The *SnowMicroPen* was used to measure the penetration resistance at a millimeter resolution by driving a 2-meter long probe vertically into the snowpack (Schneebeli et al. 1999). From the signal, the density and SSA profile can be retrieved (Proksch et al., 2015). One measurement takes about 1 to 3 minutes, which is well suited for daily investigations.

The *IceCube* is a commercial optical system for measuring the snow SSA, which was derived from the method presented by Gallet et al. (2009). In summary, it is based on the relationship between the infrared hemispherical reflectance of snow and the SSA. The surface of a 3 cm thick snow sample is illuminated by a laser diode at a wavelength of 1310 nm. Light reflected by the snow is collected via an integrating sphere and converted to voltage by a photodiode. A calibration curve, obtained using certified standards, provides the voltage-to-reflectance relationship. This reflectance is then converted to SSA using a radiative transfer model. The vertical profile of SSA at a 3 cm resolution was obtained by measuring successively the SSA of snow samples collected vertically in the snow pit.

A rectangular density cutter of 100 cm^3 and 3 cm height was used to measure density by weighing the snow contained in the cutter and assuming an ice density of 917 kg m^{-3}. The density profile was obtained by taking samples every 3 cm in the snow pit.

Traditional snow profiles included ram and hand hardness, grain size, grain shape as well as temperature profile and snow water equivalent (SWE) (Fierz et al. 2009).

X-ray computed tomography (micro-CT) was used to image snow samples in three dimensions at a resolution of 10 micrometers. Snow samples were collected in the snow pit and transported in insulated boxes filled with dry ice (about -80°C) to the SLF cold-laboratory for scanning. Based on the 3D images, we computed properties such as density, SSA, and other microstructural parameters.

The Propagation Saw Test (PST) was used to investigate fracture propagation along buried weak snow layers independently of additional loading required for failure initiation (Gauthier and Jamieson 2008). The experiments were recorded with a video camera with a frame rate of 120 frames per second. From the video recordings of the PST experiments, we derived the critical crack length, the elastic modulus of the slab, the weak layer specific fracture energy, the crack propagation velocity and finally the amount of collapse of the weak layer after fracture (Van Herwijnen et al., 2016).

2.2 *Weissfluhjoch site and measurement protocol*

The WFJ site is located in the Swiss Alps at an altitude of 2536 m (latitude 46.82963 N, longitude 9.80925 E).

Method	Vertical scale	Periodicity	Properties
SMP	1 mm	daily	Penetration force, derived: density and SSA
Cutter	30 mm	weekly	Density
IceCube	30 mm	weekly	SSA
micro-CT	0.1 mm	variable	Microstructure, numerical computations
Trad. profile	>5 mm	2 weeks	Grain shape/size, hardness, etc
PST	-	≈ weekly	Mechanical properties

Table 1. Overview of the measurements performed during winter 2015-2016.

The overview of the measurements performed during winter 2015-2016 is given in Table 1. The set up and location of the different measurements are shown in Figure 1, 2 and 3. In the course of the winter season, measurements were successively performed along a "measurement line" (Fig. 1) at 0.3 m distance from the measurements of the previous day. Each day, five SMP measurements were done. Every week, a snow pit was in addition dug to measure density with the cutter and SSA with the *IceCube* along the pit wall. Every two weeks, we also recorded a traditional snow profile in the same pit. The PST was carried out on an undisturbed area directly adjacent to the pit, almost every week starting on beginning of January. Finally, we took samples from the snow pit to monitor the evolution of the dominating weak layers in interesting periods.

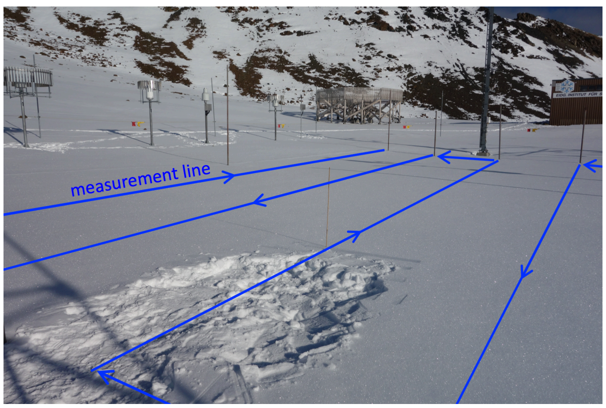

Fig. 1: Picture of the WFJ measurement site. Measurements were done following the line shown in blue.

Fig. 2: *(left)* Preparing the PST and *(right)* performing the traditional snow profile.

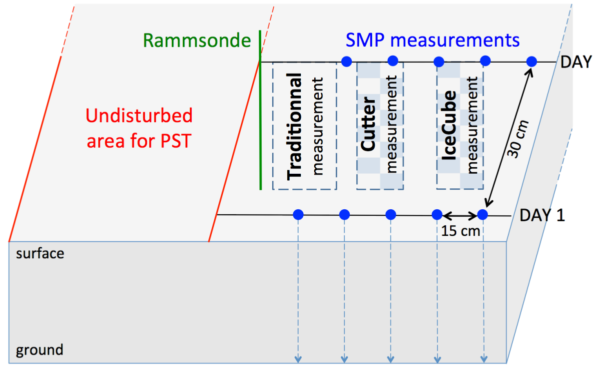

Fig. 3: Set up of the different snow measurements illustrated for two days.

3. PRELIMINARY RESULTS

While a detailed evaluation is currently in progress, a preliminary analysis on snow density is presented here to demonstrate the impact of temporal resolution.

Figure 4 shows the weakly evolution of the density profile of the snowpack obtained by the cutter measurements in the snow pit. To enable comparisons with the SMP measurements below, the persistent melt-freeze crust formed early December 2015 has been chosen as reference layer and arbitrarily assigned to zero depth.

Recent snow falls are easily identified by the presence of light snow of about 100 kg m^{-3} (blue), while denser snow of about 450 kg m^{-3} is shown in red. As an interesting feature, the bottom of the snowpack is lighter than the adjacent layers above from February on. This bottom part corresponds to depth hoar crystals, which apparently inhibit the compaction, although the snow height reached more than 2 meters at the beginning of March.

Next we compare these weekly observations to daily ones from the SMP shown in Figure 5. The height has also been re-adjusted using the same crust as reference layer as explained above. Note that these density values have been retrieved from the SMP measurements using directly the parameters given in Proksch et al. (2015) without site-specific calibration (ongoing work).

First, as an obvious advantage of the SMP measurements, thinner layers can be detected and followed in time. This is due to the difference in vertical resolution between the different measurements (3 cm vs. 1 mm). Second, daily data allows to follow more continuously the density evolution of layers during the season.

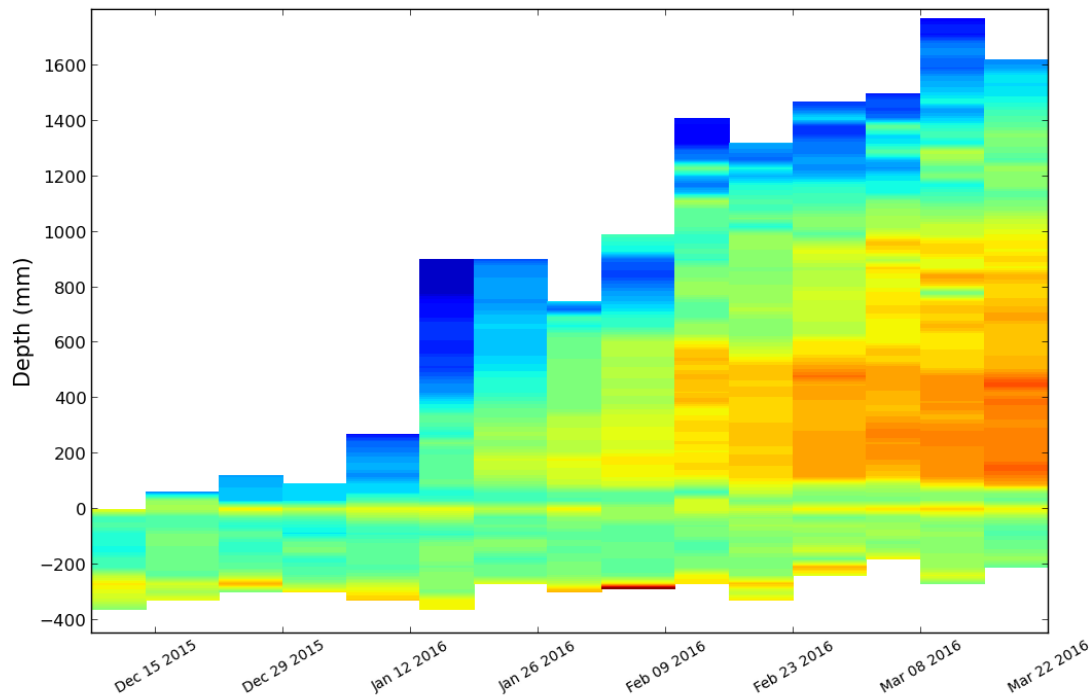

Fig. 4: Weakly evolution of the density profile of the snowpack at WFJ during winter 2015-2016 obtained by the cutter measurements.

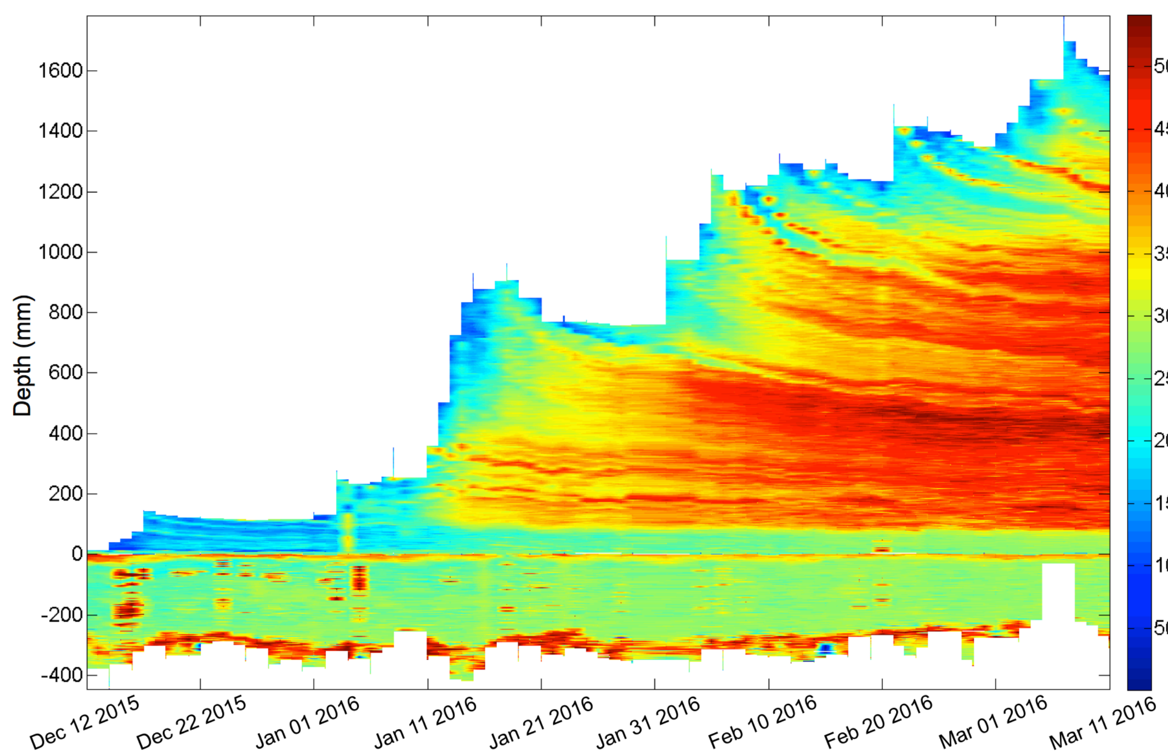

Fig. 5: Daily evolution of the density profile of the snowpack at WFJ during winter 2015-2016 derived from the SMP measurements.

For instance, we can follow the density of the fresh snow layer formed on around 16th of January of about 70 kg m^{-3} (blue), which gradually evolved toward 250 kg m^{-3} after a few days (green), to 350 kg m^{-3} around 26th of January (yellow), and finally to 450 kg m^{-3} and higher (red) after 3th of February.

Some features are consistently revealed by both methods (cutter and SMP): the layer directly above the crust, from 0 to 100 mm depth, was compacted from a density of about 150 kg m^{-3} to 250 kg m^{-3} due to the large snowfall starting on 11th of January. After that, the density remains almost constant throughout the season as a consequence of depth hoar structures.

4. CONCLUSION

We have presented an overview of the 2015-2016 measurement campaign at the high-elevation alpine site of WFJ, Davos, Switzerland. The campaign was designed to provide a time series of density and SSA, combining methods with different spatial and temporal resolutions for snowpack model evaluations. Traditional snow profiles, stability tests and micro-CT measurements complement this dataset.

The daily observations allow to follow the evolution of thin layers almost continuously, in contrast to weekly measurements. Such detailed monitoring enables a comprehensive investigation of the snowpack evolution such as densification rates. Note however that accurate estimates of density and SSA from SMP measurements rely on a local calibration, which was not done yet in this paper.

Daily monitoring is time consuming and the temporal resolution of measurements should be chosen depending on the application. Our preliminary comparison showed that some features are consistently revealed using weekly or daily measurements, e.g. the low densification of the bottom part of the snowpack.

In combination with high quality meteorological and radiation data available at the WFJ site, this unique set of objective measurements will contribute to improve our understanding of snow-cover processes, ranging from metamorphism to mechanical stability, and guide the development of next generation snow-cover models.

ACKNOWLEDGEMENTS

We would like to acknowledge M. Proksch and B. Reuter (SLF), who have initiated the daily SMP measurements project. We also acknowledge the PhD students of the SLF that have performed the daily SMP measurements of this study.

REFERENCES

Bartelt, P., and Lehning, M., 2002: A physical SNOWPACK model for the Swiss avalanche warning: Part I: numerical model. *Cold Regions Science and Technology*, *35*(3), 123-145.

Carmagnola, C. M., Morin, S., Lafaysse, M., Domine, F., Lesaffre, B., Lejeune, Y., Picard, G., and Arnaud, L., 2014: Implementation and evaluation of prognostic representations of the optical diameter of snow in the SURFEX/ISBA-Crocus detailed snowpack model, *The Cryosphere*, 8, 417-437.

Essery, R., Kontu, A., Lemmetyinen, J., Dumont, M., and Ménard, C. B., 2016: A 7-year dataset for driving and evaluating snow models at an Arctic site (Sodankylä, Finland), *Geosci. Instrum. Method. Data Syst.*, 5, 219-227.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A, 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.

Gallet, J. C., Domine, F., Zender, C. S., & Picard, G., 2009: Measurement of the specific surface area of snow using infrared reflectance in an integrating sphere at 1310 and 1550 nm. *The Cryosphere*, *3*(2).

Gauthier, D., and Jamieson, B., 2008: Fracture propagation propensity in relation to snow slab avalanche release: Validating the Propagation Saw Test. *Geophysical Research Letters*, *35*(13).

Morin, S., Lejeune, Y., Lesaffre, B., Panel, J. M., Poncet, D., David, P., and Sudul, M., 2012: An 18-yr long (1993–2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325 m alt.) for driving and evaluating snowpack models. *Earth System Science Data*, 4(1), 13-21.

Morin, S., Domine, F., Dufour, A., Lejeune, Y., Lesaffre, B., Willemet, J. M., Carmagnola C.M., and Jacobi, H. W., 2013: Measurements and modeling of the vertical profile of specific surface area of an alpine snowpack. *Advances in Water Resources*, 55, 111-120.

Pinzer, B. R., M. Schneebeli, and T. U. Kaempfer (2012), Vapor flux and recrystallization during dry snow metamorphism under a steady temperature gradient as observed by time-lapse micro-tomography, The Cryosphere, 6(5), 1141–1155.

Proksch, M., Löwe, H., & Schneebeli, M., 2015: Density, specific surface area, and correlation length of snow measured by high-resolution penetrometry. *Journal of Geophysical Research: Earth Surface*, *120*(2), 346-362.

Proksch, M., Rutter, N., Fierz, C., and Schneebeli, M., 2016: Intercomparison of snow density measurements: bias, precision, and vertical resolution. *The Cryosphere*, *10*(1), 371-384.

Schneebeli, M., C. Pielmeier, and J. Johnson, 1999: Measuring snow microstructure and hardness using a high resolution penetrometer, *Cold Reg. Sci. Technol.*, *30*(1–3), 101–114.

Stössel, F., M. Guala, C. Fierz, C. Manes, and M. Lehning, 2010: Micrometeorological and morphological observations of surface hoar dynamics on a mountain snow cover, Water Resour. Res., 46, W04511.

Van Herwijnen et al., 2016: Measuring the mechanical properties of snow relevant for dry-snow slab avalanche release using particle tracking velocimetry, In *Proceedings ISSW 2016*.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin E., and Willemet, J. M., 2012: The detailed snowpack scheme Crocus and its implementation in SURFEX v7. 2. *Geoscientific Model Development*, *5*, 773-791.