2nd Winter Snow School
Group 8 – Report

Max Stevens, Laura Thomson, Rebecca Vignols, Tomasz Wawrzyniak

I. Introduction:

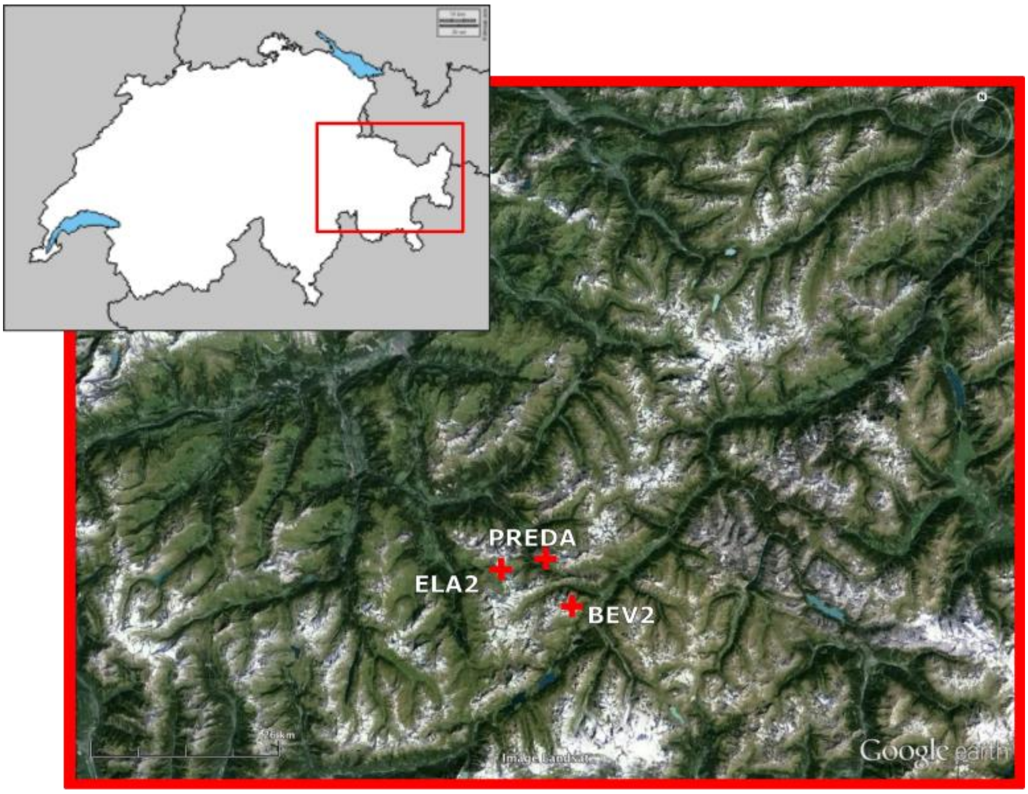

Figure 1: Switzerland base map and aerial photograph showing the location of the three weather stations used in this report: Preda (where field measurements were made), BEV2 and ELA2.

As part of the 2nd Winter Snow School, we spent a week in Preda, located in the Eastern Swiss Alps (Fig.1) at an altitude of 1650m.

There, we learned how to use field techniques to measure the physical properties of snow. We were taught traditional techniques as well as how to use the latest precision instruments such as the Snow MicroPen (SMP), IceCube and IRIS.

Field measurements were made over the four days from 16/2/16 to 19/2/16. Meteorological data from nearby stations for the two weeks prior to and the week of the course are shown in Figure 3. In the field we studied the snow at three different sites: an open (non-forested) site below the tree line, a forested site very close to the open site, and a site along a slope above the tree line at 2130 m (Fig. 2).

In this report, we discuss the spatial variability of snow-pack properties in an Alpine setting.

First, we discuss the variability observed in data from snow pits across the three sites. We then consider variability in snow-water equivalence (SWE); this section emphasizes mostly the effects of forest-snow interactions. Finally, we compare SNOWPACK model outputs to our field measurements.

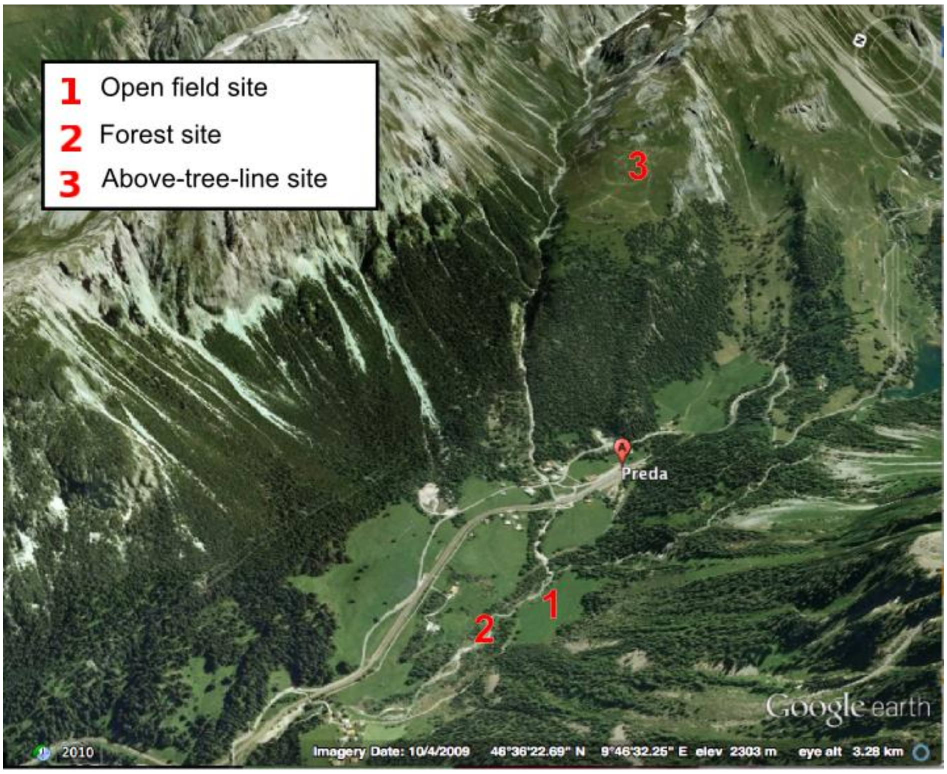

Figure 2: Aerial photograph of the Preda area showing the location of the three field measurement sites.

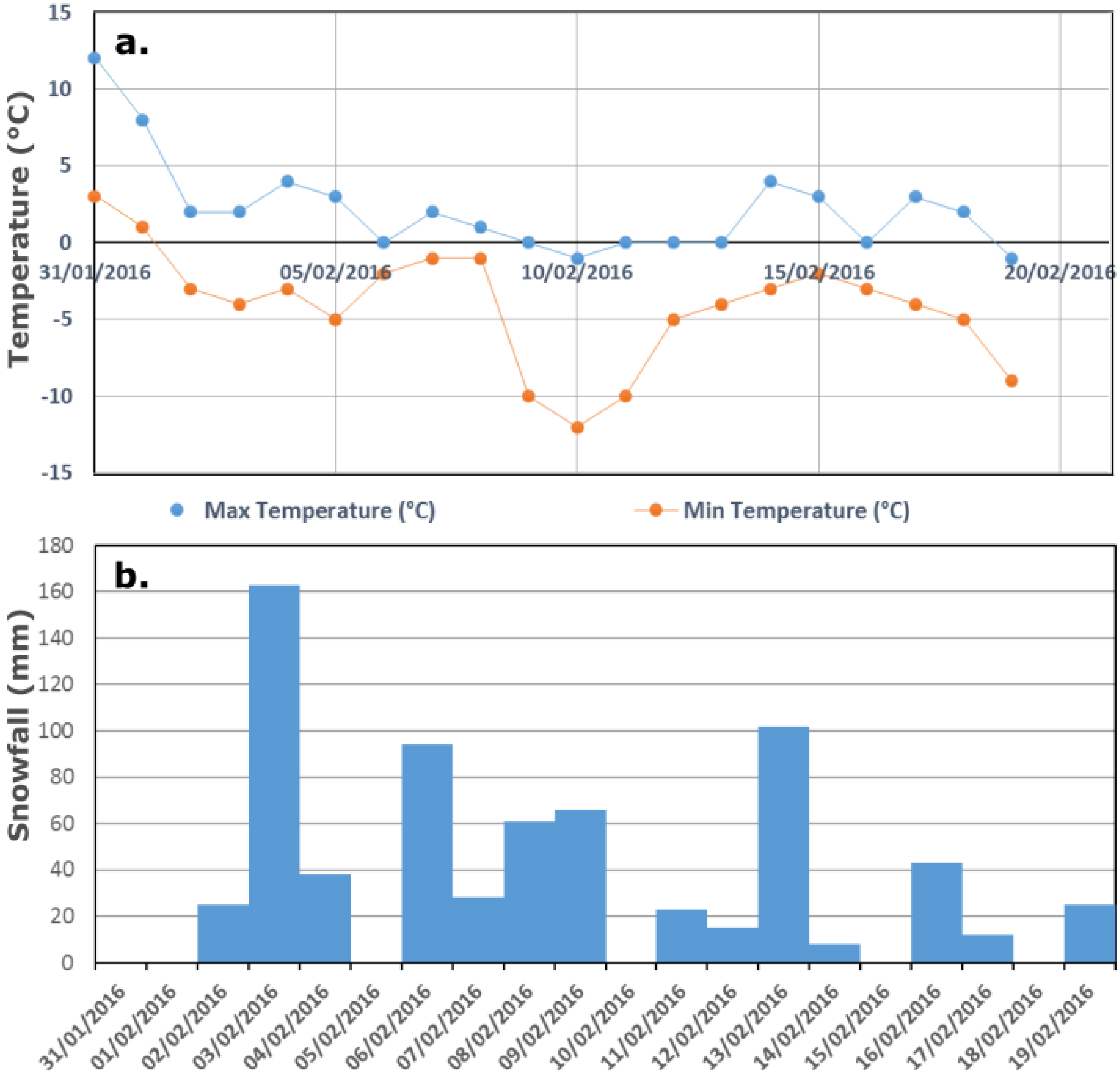

Figure 3: Meteorological data of Preda from the start of the month of February until the end of the snow school. a. shows the daily maximum and minumum air temperatures in °C; b. shows the daily amount of snowfall in mm.

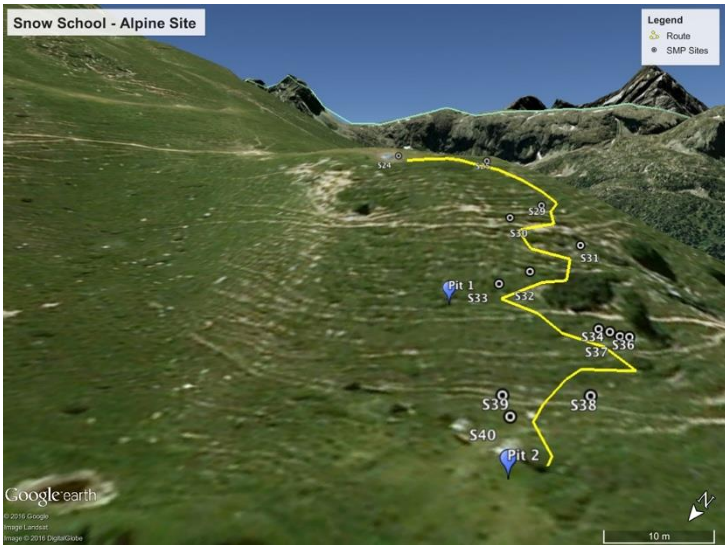

Figure 4: Map of the above-treeline study area

II. Snow pit results:

We dug six snow pits in total: two at the above-treeline site, three in the forested site, and one in the open site. We also used the SMP to measure snow-penetration resistance at 17 locations along a path at the above-treeline site. Figure 4 shows the locations of the path, two pits, and SMP on a NW facing slope at the above-treeline site. The forested site pits were (1) ~ 5 m south of a large spruce tree, (2) ~5 m north of the same tree, and (3) under a larch tree. We used the SMP to measure penetration resistance 6 times at the open site; the SMP measurements were spaced ~40 cm apart.

In each of our snow pits, we measured snow temperature, hardness, grain size, and grain type. We recorded layer interfaces, and in some pits we measured density with a cutter-type measurement system.

Figure 5 shows the measurements from 4 of the 6 snow pits. All of the snow pits had some qualitative similarities, but there was much variability in the snowpack at several spatial scales. The similarities included the presence of a depth-hoar layer at the base of the snowpack, rounded grains near the surface, and faceted grains in the middle of the snowpack. We also observed a hard, icy layer just above the depth hoar.

The spatial variability and similarities on the valley scale includes the snow depth, which ranged from 31 cm underneath a tree to 104 cm at one of the above-treeline pits. The other 4 pits were roughly 60 cm deep. These results are not surprising; we expect that the mesoscale climate is the same for each of the sites, and the snowpack broadly reflects the weather history of the region. However, local controls including topography, aspect, forest cover, and elevation have an effect on the microclimate and thus the snowpack properties.

We observed smaller-scale spatial variability at all three sites. The two forest pits were separated by ~10 m. The snow in each of these pits was of similar depth, but the layers differed. In the pit north of the tree, which we expect to be in the shade more frequently, the surface snow was decomposing and fragmented precipitation particles, whereas the surface grains in the south pit were rounded. The grain size in the upper layers of the south pit were larger than those in the

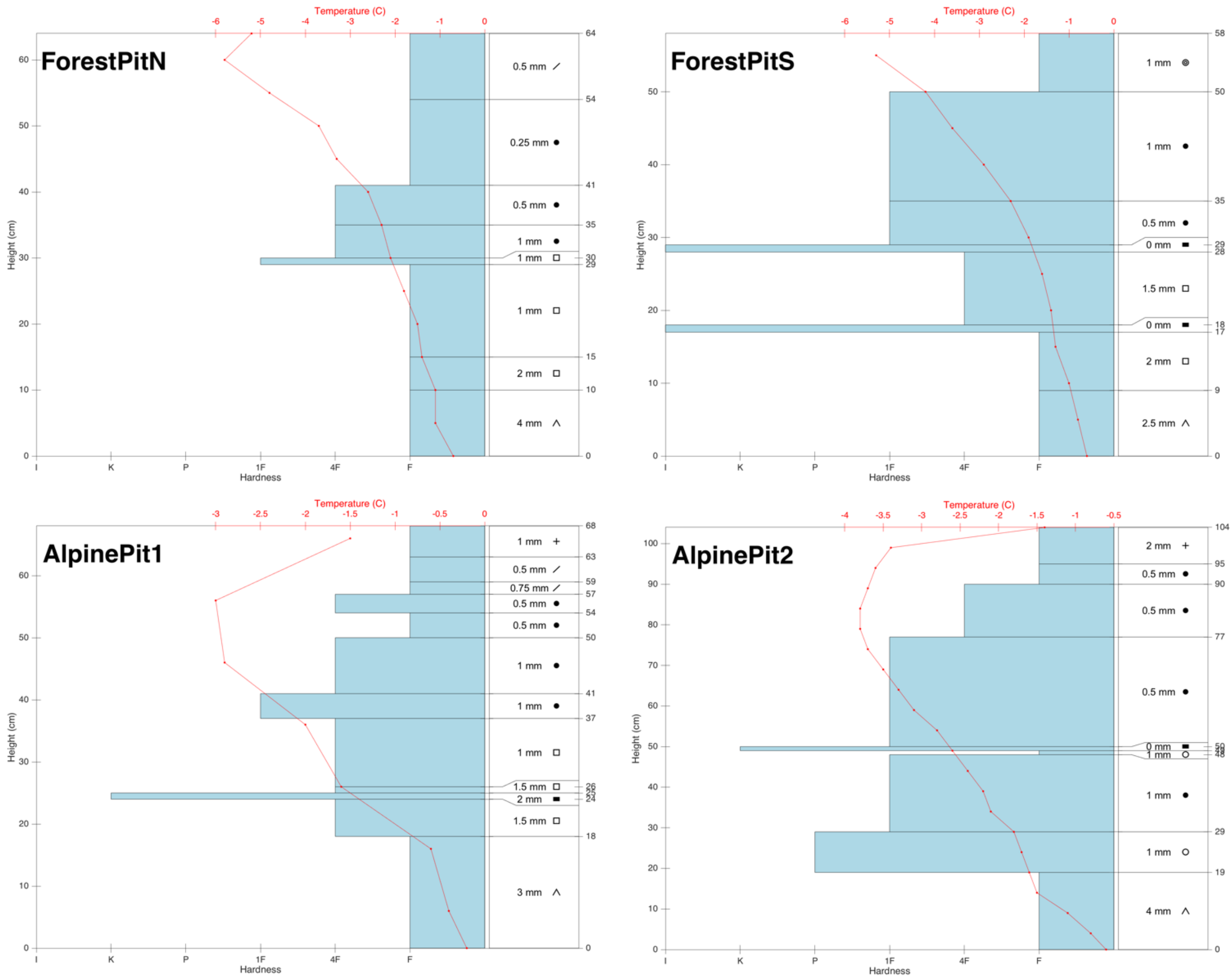

Figure 5: Physical properties measured in 4 of the snow pits. See the International classification for seasonal snow on the ground (Fierz et al., 2009) for description of grain symbols.

north pit, which may be due to faster metamorphism resulting from more shortwave energy input. We observed ice layers in both the north and south pits at approximately 30 cm above the ground, but the south pit also had an ice layer 17 cm above the ground. We infer that this layer could have been created as a surface melt layer on a warm, sunny day; the south pit would have had enough direct solar energy to form this melt layer, but the shaded north pit would not have.

At the above-treeline site, our two snow pits were separated by ~40 m. Pit 1 was ~20 m higher in elevation than Pit 2. The snow was significantly deeper at Pit 2, which was at the bottom of the slope. Snow depth at the top of the local topographic high was less. It is not immediately clear if the slope is on the lee or windward side, but regardless we hypothesize that the prevailing winds at this location preferentially deposit snow on the lower portions of the slope. We observed ice lenses at 24 cm in Pit 1 and 49 cm in Pit 2. These lenses could be from different events, but likely they were formed at the same time on the surface as either a rain or melt crust; the layer is higher above the ground in Pit 2 because more snow falls at that location and the surface was higher when the crust formed.

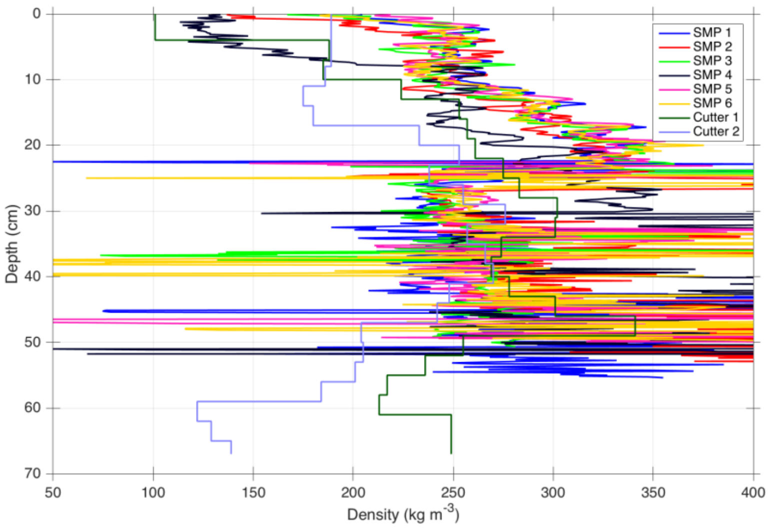

Figure 6: Depth-density profiles measured in the open-area pit with cutters and with the SMP.

We also examined spatial variability on the scale of tens of centimetres in the open-area snow pit. Figure 6 shows 2 density profiles measured on the same pit wall using the cutter, and it also shows density profiles calculated from the SMP measurements using the equations from Proksch et al. (2015). The two cutter measurements are variable through the entire snowpack; “Cutter 2” is low compared to “Cutter 1”. Both cutter measurements are lower than the SMP-converted densities. Within the SMP densities we observe generally consistent densities near the surface with a relatively small amount of variability. Deeper in the snow, the signal appears to be very noisy; some of the predicted densities are negative, which is not physical. We attribute some of the variability in the density measurements to real spatial variability and some to instrument noise, but we do not attempt to quantify the instrument uncertainty here. The difference between the cutter densities and SMP densities is likely a sampling error. Potentially the cutter could have not been full for some of the samples. The equation that we used to convert penetration force to density was developed for a different version of the instrument, and that equation may not apply for the newer instrument we used. Additionally, the program used to pick the surface and bottom of the snowpack relies on a human choosing the depth he or she thinks is that interface.

All of our snow pit measurements have some amount of sampling error. The difference between the two cutter profiles could be due to spatial variability, but it is likely due to error in sampling. All of our measurement uncertainty is increased due to the fact that we had different team members making measurements with their own individual techniques. For example, what one person defines as a layer another person may not. Grain sizes and shapes are not perfectly homogenous within a layer, and it is up to an observer to determine the representative grains. Therefore, we infer that a significant amount of the spatial variability we observe, especially on small scales, is due to inherent uncertainty.

III. Snow-water equivalent:

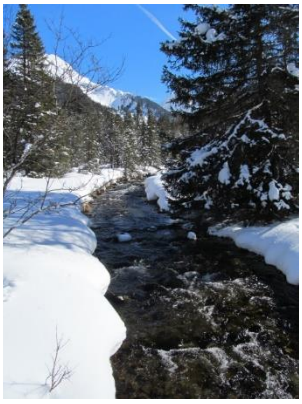

Fig. 7: Albula River

In this section we provide an evaluation of changes in the SWE in different altitude zones and in complex land cover types (forested and open). Thickness and physical properties of snow cover are a combination of precipitation, air temperature, wind, elevation, slope, aspect, exposition, solar radiation and many other factors. The hydrological significance of snow cover is characterized by the snow water equivalent (SWE), as it provides information about the amount of water in a given snow-covered area (Jonas *et al.*, 2009). In mountainous catchments with seasonal snowpack (as in Preda), changes in snowpack and duration of snow cover cause changes in the water regime. In alpine regions snowmelt provides a dominant contribution of the total runoff., so Measurements of spatial and temporal distribution of snow in watersheds are vital for proper water balance calculations. Monitoring of SWE distribution is especially important for forecasting of snow and rain-snow induced floods and estimates of water resources. Spatial and temporal estimates of water storage in snowpack are limited due to the extreme spatial variability of snow cover (McCreight and Small, 2014).

Our measurements were made in the basin of the Albula river. The river itself is 36 km long and the whole catchment area covers 950 km^2. The first site was located above the tree line at 2130 m a.s.l. on one of the ridges of Piz Üertsch. Second and third sites were located next to each other at 1830 m a.s.l. in the close surroundings of Preda.

We conducted measurements of snow cover thickness, bulk density, SWE and physical properties using provided equipment (snow density kit, snow density tube/corer). To gain more insight into the snow properties we dug several snow pits. From snow pits we obtained vertical profiles of snow density (using a wedge cutter), temperature and grain size. The analysis was focussed on slab properties, weak layer properties (facets and depth hoar) and their interactions. An example of snow pit data collected at different locations is presented in Figure 5. To obtain estimates of bulk density in more points we used less time consuming than snow pit method - snow corer. The snow corer was inserted into the snow until it contacted the ground, and the resulting snow core was removed and weighed. Bulk snow density estimates from snow corers were almost identical

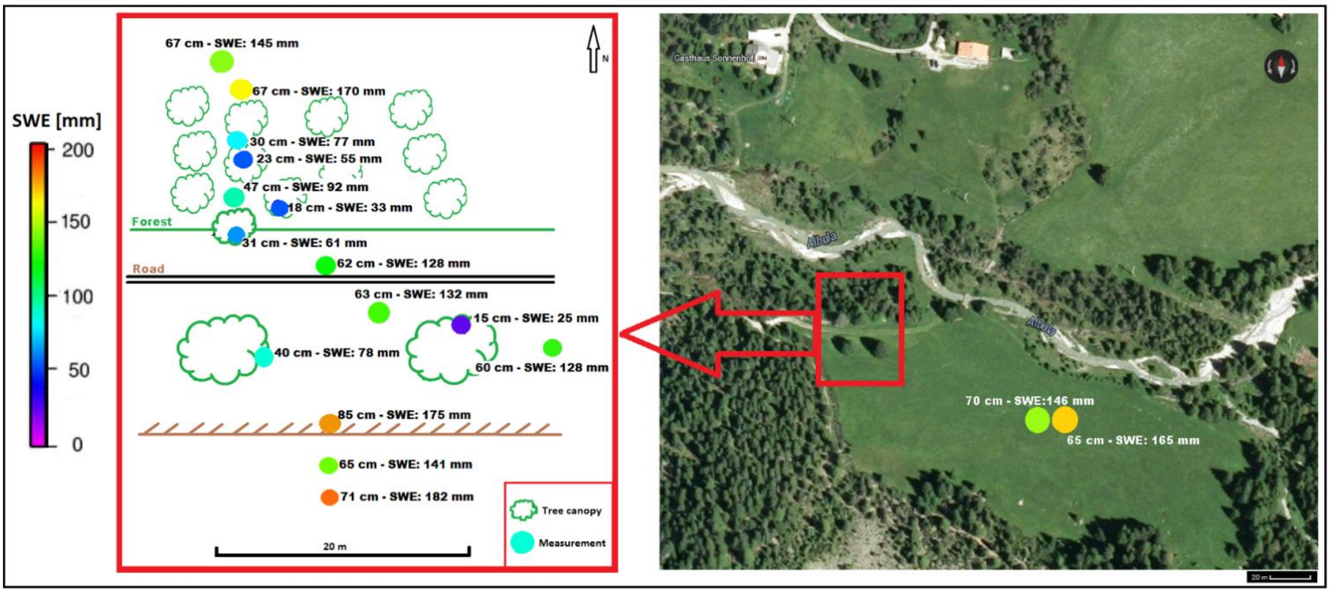

Fig. 8: SWE at open sites and under tree canopy.

to those obtained by sampling snow profiles using a wedge cutter in snow pits in the same points.

Given the complex topography and frequent snow redistribution processes in alpine environments, SWE typically displays a considerable spatial variability even within a given sample site (Rutter *et al.* 2014). Not surprisingly, there are considerable differences between snow depths and densities

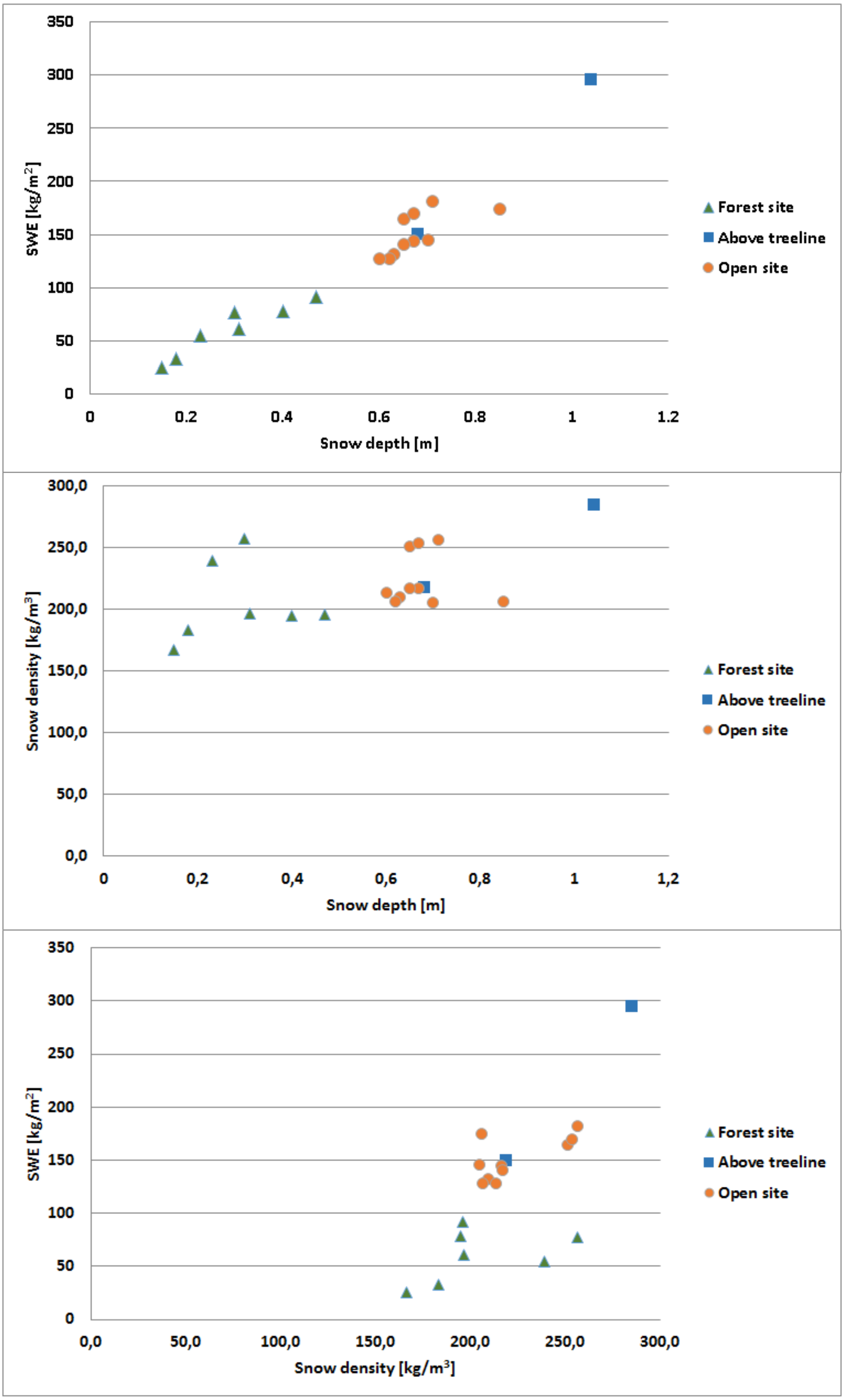

Fig. 9 The relationships between SWE, density and snow cover thickness.

between sites and within them. Figure 8 shows the spatial distribution of SWE and thickness at forest and open field sites. Field study allowed us to understand the processes that control snow accumulation and melt in areas unaffected by forest canopies and in places where snow is controlled by interception of forest canopies. Obtained results reveal much thinner layer of underneath-canopy snowpack.

Snow depth, bulk density and water equivalent are related to one another. Their relationships at different locations is presented in Figure 9. All sampling points show that SWE is strongly correlated to the snow depth. Their correlation seems approximately linear. The highest thickness 104 cm, measured on flat surface above tree line at the bottom of the slope, has also the highest SWE. The altitude has a direct effect on the amount of precipitation (higher elevations usually get more snow), although not without significance is also the slope rating. On the steep slope at ~2150 m a.s.l. the thickness of snow was similar to thickness obtained at flat surface of open sites, located almost 400 meters lower. Bulk density is related to the snow thickness although ranges the most in shallow snow cover from low-density new snow to higher-density of compacted or wet snow. At forest site this can be probably explained by melting of snow on the tree canopy branches, which produces slush snow beneath.

IV. Using the SNOWPACK model:

The SNOWPACK model, developed by SLF (Bartelt & Lehning, 2002; Lehning et al., 2002a; ; Lehning et al., 2002b), was used to compare simulated snowpack conditions at two stations near Preda with our *in situ* observations made at the 'Open Site.' SNOWPACK was run using input meteorological data collected from to following two stations:

(1) ELA2: Located 4.6 km west of Preda at an elevation of 2725 m, near the Piz Ela,
(2) BEV2: Located 7.2 km southeast of Preda at an elevation of 2510 m, near Samedan.

The model input includes weather station data with a temporal resolution of 30 minutes (based on *.smet files), and is capable of initializing with previously known information about the snowpack (*.sno files). For both ELA2 and BEV2 the *.sno files indicate that no snow was on the ground at the beginning of either simulations (August 1, 2015). For each station the model was run through to the final observation date (8:30 am, February 23, 2016) and the resulting output files (*.pro)

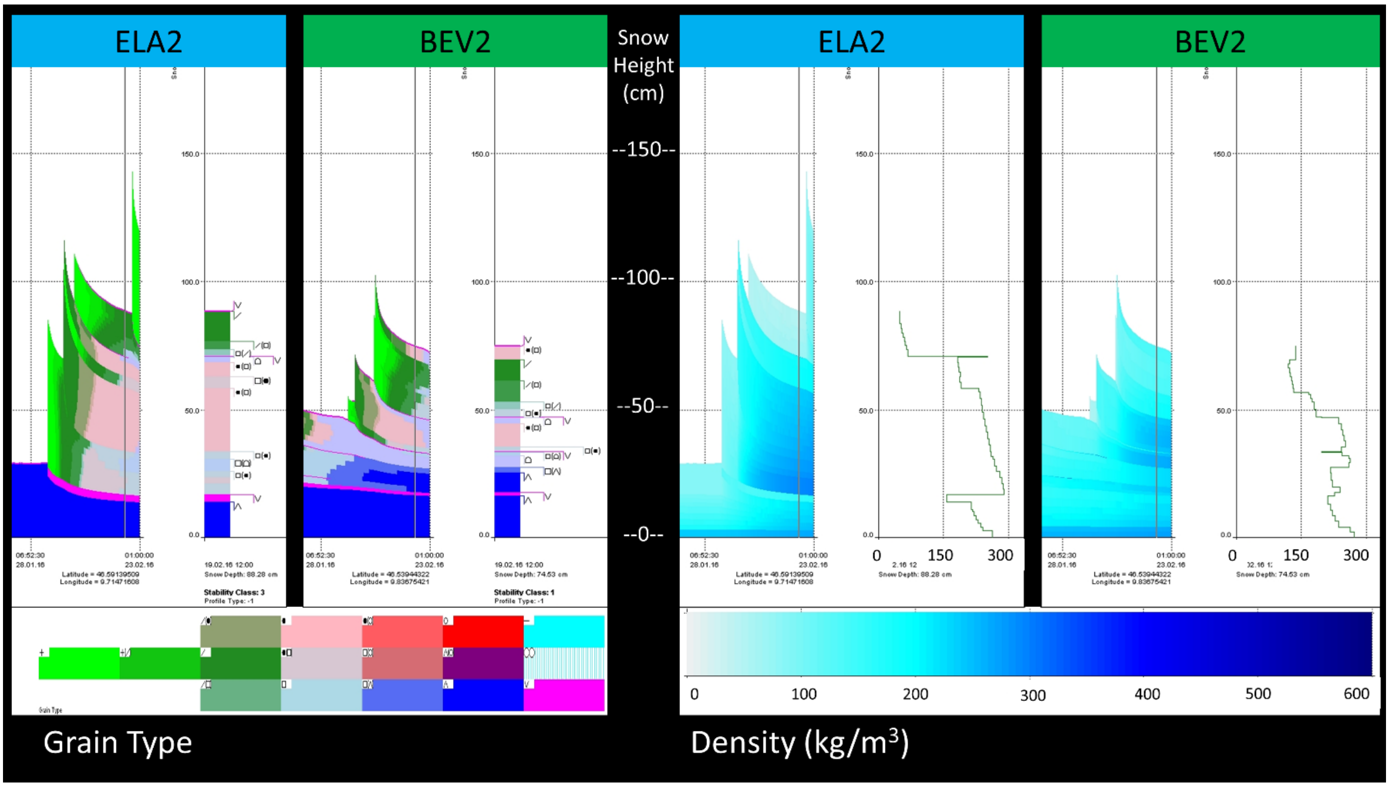

Figure 10. SNOWPACK results showing grain size (left) and density (right) results for the ELA2 and BEV2 stations, with snowpack profiles for February 19th at 2:00pm show on the right of each plot.

were viewed using the visualizer in sngui (version 8.4). The visualizer enables the user to view a range of snowpack properties (e.g. temperature, density, grain size and type, etc.) as well as the meteorological input data used to run the model (Figure 10). The user can also select a specific date and time to produce a profile of the properties for a given date and time, which we show for February 19th at 2:00pm, the approximate time that our observations at the Open Site were conducted.

Site & Elevation	Depth (cm)	Max. Density (kg m^{-3})	Min. Density (kg m^{-3})	SWE (mm w.e.)	Weak layer height (cm)	Hard layer height (cm)
ELA: 2725 m	88.22	380 (22 cm)	60 (sfc)	177.13	20	23, 32
BEV: 2510 m	74.47	260 (base)	130 (sfc)	151.52	21	30, 63
Open: 1650 m	67	340 (17-22cm)	100 (sfc)	155.5	20	18, 30

Table 1. Comparison of observed and modeled snowpack properties.

In comparison with the Open Site, both ELA2 and BEV2 showed higher snow depths which may be related to their higher altitude, cooler temperatures, and the initiation of the continuous high-altitude winter snowpack during a snowfall event that occurred at both sites on September 23rd, 2015. In Preda, this precipitation event was observed but daily temperatures in Preda remained above 0°C through much of October 2015, so if the precipitation fell as snow it would have melted. Regarding the density profiles, ELA2 demonstrates a relatively steady increase in density (suggesting steady compaction) beneath the low density surface snow, with a break in this trend at 20 cm above the surface, which is followed by a drop in density and subsequent increase to the base. The BEV2 model similarly shows an increase in density with depth, but the profile is more varied suggesting the snowpack was subject to periodic melt and possibly percolation events, which might be expected for sites lower than ELA2. The surface snow density is much lower at the ELA2 site that the BEV and open sites, this is also likely due to the higher altitude. One common feature is that all three sites demonstrate a weak layer of buried surface hoar at ~20 cm above the surface, as well as depth hoar at the base. Considering these facts, we conclude that modeled snowpack at BEV2 is likely a better representative of the snowpack observed at the Open Site, despite being further away, than the snowpack at ELA2. This may suggest that elevation, which is closer between Open and BEV2 than Open and ELA2, is a more meaningful indicator of snowpack evolution than vicinity.

V. Snow Albedo Measurements

At the Open Site, we also experimented with the nadir and zenith pointing radiometer instrument

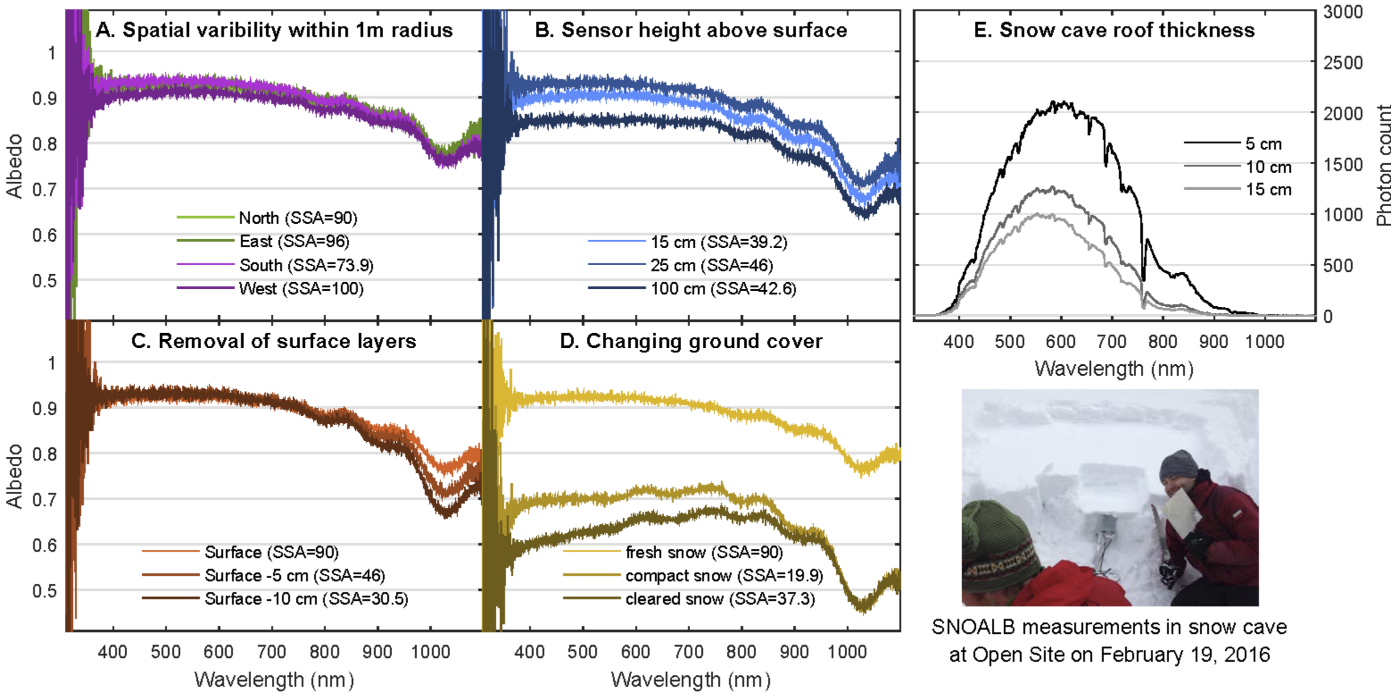

Figure 11. Snow albedo measurements at the Open Site.

provided by Marie Dumont. We conducted a series of experiments (results plotted in Figure 11) to test A) the spatial variability of surface albedo within a 1 m radius; B) the impact of changing sensor height above the surface; C) the change in albedo at different depths by removing layers of snow from the surface; and D) the albedo of the ground as it changed from undisturbed snow, to compact snow, to cleared ground. We also excavated a small snow cave at the base of the snowpack and measured how the photon count changed as we removed surface layers (E), which demonstrated the transmittance of light through the snowpack.

V. Conclusions:

The Winter Snow School enabled us to improve our understanding of snow cover observations and interpretation. The main goal of our analyses was to understand the spatial distribution of multiple snow properties including thickness, bulk density and SWE at three different locations. Altitude and slope were found to have a high impact on precipitation and thus snow depth. We showed that SWE is highly spatially variable and is strongly correlated with snow depth. As expected, snow depth was found to be lower in forested areas, where a higher proportion of the falling snow can be lost by sublimation. Some bulk properties of snow were consistent on the valley scale, indicating that the mesoscale weather phenomena in the area have a large control on the snowpack. Snow pit measurements have inherent uncertainty due to sampling errors and differences among observers.

In comparing our *in situ* snow pit data with models of the ELA2 and BEV2 stations using SNOWPACK, we concluded that the BEV2 station better represents snow conditions near Preda than the higher elevation, but closer, ELA2 station.

VI. References

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