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Influence of forest on snow properties in Oslo, Norway

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Abstract

Increased knowledge on how forests influence snow in Norway is essential in avalanche hazard assessments and for snow hydrology in general. Field measurements are necessary to get more insight into the influence of forests on snow. However, as gathering data in the field is time–consuming, a possible supplement is to include simulations of the forest effect on snow cover. This study aims to compare field observations of the snow cover in the forest outside of Oslo, Norway, to snowpack simulations. The simulations considered the forest effect by modifying the incoming radiation. Field measurements were conducted in January and February 2022 and involved snow pit profile measurements. Data on snow depth, temperature, stratigraphy, hardness, and shear strength of observed weak layers were gathered in the forest and outside. The observations were then compared to the simulations. Certain distinct similarities between the simulated and observed snowpack were observed, i.e., the timing of snowfall, appearance of certain grain types, and temperature. The number of field measurements was insufficient to state a significant similarity between the simulations and measurements, thus implying that more data on this is needed. However, some of the findings are worth considering, such as differences between forest cover in different parts of forest openings.

Økt kunnskap om hvordan skog påvirker snøen i Norge er vesentlig i videreutvikling av skredfarevurderinger og for snøhydrologi generelt. Feltmålinger er nødvendig for å få mer innsikt i skogens påvirkning på snø. Ettersom det er en tidkrevende prosess å samle data i felt, er et mulig supplement å inkludere simuleringer av skogeffekten på snødekket. Denne studien tar sikte på å sammenligne feltobservasjoner av snødekket i skogen utenfor Oslo, med snødekkesimuleringer. Simuleringene tok for seg skogeffekten ved å modifisere den innkommende strålingen. Feltmålinger ble utført i januar og februar 2022 og omfattet snøgropmålinger. Data om snødybde, temperatur, stratigrafi, hardhet og skjærstyrke for observerte svake lag ble samlet i skogen og utenfor. Observasjonene ble deretter sammenlignet med simuleringene. Visse distinkte likheter mellom den simulerte og observerte snøp ble observert, dvs. tidspunktet for snøfall, korntyper og temperatur. Antall feltmålinger var utilstrekkelig til å angi en signifikant likhet mellom simuleringene og målingene, noe som betyr at det er behov for mer forskning dette. Noen av funnene er imidlertid verdt å vurdere, som for eksempel forskjeller mellom skogdekke i ulike deler av åpne områder.

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CHAPTER 1

Introduction

1.1 Motivation and aim

Avalanches are a threat to people and infrastructure. Throughout the years, different mitigation measures have been developed to limit the risk, e.g., protection forests and hazard indication maps. Protection forests are not as widely used in Norway as in other countries where avalanching also is a problem (the Alps, North–America). On the other hand, Avalanche hazard maps have been used in Norway since the 1970's (Issler et al., 2020). Combining hazard indication maps with knowledge of the forest effect on avalanches can contribute to a more detailed understanding of where avalanches occur and a more precise hazard assessment.

There are mainly four processes in which the forest affects the snow cover; interception of snow by the tree branches, lowering of wind speeds, altering of the energy balance, and anchoring of the snowpack (Bebi et al., 2009). The first three are relevant for this thesis, whereas forests' anchoring effect on the snowpack will not be considered. Interception and lower wind speeds in the forest both have a stabilizing effect on the snow cover. Both effects lead to less snow in the ground, and lower wind speeds can also inhibit the creation of weak interfaces that can cause avalanches. Changing the energy balance also increases the stability in forest snowpacks (Gubler and Rychetnik, 1991). However, more research on the effect of forests on avalanches in a Norwegian setting is needed (Breien and Høydal, 2015).

Avalanche hazard indication maps (AHIM) have been used to assess the avalanche hazard in Norway since 1975, and NGI (Norwegian Geotechnical Institute) has been responsible for providing these maps in Norway. There have been made two versions of the AHIM, both with different approaches. The first generation (AHIM–1G) was made manually and included forest and climate; however, it only covered selected areas. The second generation, AHIM–2G, was made by NGU (Norwegian Geological Survey (Undersøkelse in Norwegian)) and NVE (The Norwegian Water Resources andEnergy Directorate). It was done automatically without quality control, using a very primitive topographic model combined with the α-β model. Several weaknesses with the second approach were soon discovered. One of these weaknesses was that the effect of forest on release probability and run-out distance was neglected. It was decided that an improved third generation of AHIM was needed, with one of the general goals being to focus on forest and climate effects (technical note 20150457-10-TN, Issler et al., 2018). One of the goals for the most recent edition is to include the effect of forests on avalanche hazards. NGI is making a new set of avalanche hazard indication maps in Norway through the project NAKSIN(Nye Aktsomhetskart for Snøskred I Norge, English: New avalanche hazard indication maps in Norway). (Issler et al., 2020). Thus, a more detailed understanding of the forest effect is needed to incorporate it realistically.

Quantifying the effect of forests on avalanche probability can be a great benefit when producing avalanche hazard indication maps. Forest effects on avalanches have been studied in the European Alps (Bauerhansl et al. 2010) and in North America (Weir 2002, Frey and Salm 1990). Extreme avalanches (fracture height 0.8 – 1.5 m) could start in openings extending 30 m downslope and 15 m wide. For certain forest types, such as larch, this size of opening does occur in avalanche terrain, especially near the treeline (Gubler and Rychetnik, 1991). That said, smaller avalanches might form in smaller openings than mentioned.

1.2 Aim of the study and research question

The aim of this study is to investigate how forests impact the snow cover in the forest outside of Oslo, Norway, and to evaluate the possibility of simulating this impact using numerical modeling. The work is divided into two main parts; fieldwork and snowpack simulations. Fieldwork was conducted in January–February 2022 at two different sites. The next goal is to assess whether or not the snowpack simulations are able to reproduce the differences that were observed in the field. Based on this, the following research questions have been formulated:

- What differences are observed between the snowpack in the open and in the forest in Nordmarka?
- How can simulations of the snowpack be used to recreate these differences?

CHAPTER 2

Background

In order to understand the processes in which forests affect avalanche formation, it is helpful first to understand the processes that contribute to avalanche formation in terrain without forests. It is also essential to understand the snow cover processes, which can potentially lead to avalanche formation under certain circumstances. Based on this reasoning, the background chapter will begin with an explanation of how energy and mass are transferred to snow, followed by the resulting processes within the snowpack, and after that, how these processes can lead to avalanche formation. Lastly, the effect of forests on the introduced processes is explained.

2.1 Snow pack interaction with surroundings

2.1.1 Snow energy balance

The energy balance in the snowpack is dependent on the processes happening at the boundaries of the snow, i.e., at the interface between the snow surface and the air and the interface between the bottom of the snow and the ground interface. To be able to calculate the energy exchanges at these interfaces, certain boundary conditions are used. In CROCUS, the Neuman boundary condition is used,

$$k_s \frac{\delta T_s(z = h, t)}{\delta z} = q_{lw} + q_{sh} + q_{lh} + q_{rr} \tag{2.1}$$

where k_s is the thermal conductivity of snow, T_s is the temperature of the snow, q_{lw} is net long-wave radiation, q_{sh} is the sensible heat exchange, q_{lh} is latent heat and $q_r r$ is heat from rain (Bartelt and Lehning, 2002).

Shortwave radiation is radiative energy emitted from the sun. The amount absorbed by the snowpack depends on the albedo of the surface, i.e., how much of the sunlight is reflected. E.g., snow has a higher albedo than forest, which means that the forest absorbs more of the incoming longwave radiation from the sun and can thus contribute to increased warming of the surface.

Longwave radiation is the radiation emitted by all objects above absolute zero. The amount of radiated heat depends on the object's temperature and emissivity.

Latent heat is the energy-related to phase changes. When water goes from one phase to another, heat will be released to or taken from the surroundings. During evaporation, melting, and desublimation, the water takes up heat from the surroundings. During condensation, melting, and sublimation, the water releases heat. Sublimation and desublimation are when water changes directly from solid to vapor and vapor to solid, respectively (DeWalle and Rango, 2008).

Sensible heat is energy exchange related to differences in temperature.

At the ground interface, the Dirichlet boundary condition is used,

$$T(z = 0, t) = T_g(t) \tag{2.2}$$

where T_g is the ground temperature, which does not vary significantly from zero.

2.1.2 Temperature and vapor gradients in the snowpack

Temperature gradients are the primary driver of processes happening in the snowpack. This is because temperature gradients influence the vapor pressure gradients, which again control the flux of water vapor between molecules. High-temperature gradients can occur close to the surface and cause metamorphism of snow molecules, which will be explained later (Colbeck, 1989; Fukuzawa and Akitaya, 1993).

We refer to the absolute value when talking about the magnitude of temperature gradients. This is important as, e.g., a low-temperature gradient will be closer to zero than a high-temperature gradient and not necessarily lower than zero. The intensity of snow metamorphism is dependent on the magnitude of the gradient and not in which direction it goes.

2.2 Snow processes

Snow crystals initially form in the atmosphere under low temperatures and high humidity. Snow often appears near its melting point and is therefore considered thermodynamically active, meaning it can easily change into other forms. As a result, significant changes can happen in the snowpack. Snow processes categorize how snow reacts to variable factors such as temperature, air- and snow moisture, and precipitation.

2.2.1 Snow metamorphism

There are different ways to classify snow metamorphism. In this part, metamorphism is divided into constructive and destructive. Metamorphism happens as a result of energy and mass exchange between water molecules. The temperature regime in the snow decides if the metamorphism is destructive or constructive.

2.2.1.1 Equilibrium growth

Equilibrium growth, also known as isothermal- or destructive metamorphism, happens when temperature gradients in the snowpack are small(< 5 degrees/m).

When no strong temperature gradient is found in the snowpack, the most considerable vapor pressure gradient often exists on the crystal surface. The surface will have different vapor pressure depending on the shape because of the position of water molecules. Vapor pressure will be high on areas sticking out and lower at troughs on the surface. This is due to the radius of curvature. Consequently, the molecules move from convex areas of the crystal towards concave ones, resulting in rounded grains (Sommerfeld and LaChapelle, 1970).

2.2.1.2 Kinetic growth

Kinetic growth, also known as constructive metamorphism, happens when the temperature gradient is the primary driver of molecule movement. Typical grain forms that result from kinetic growth are faceted crystals and depth hoar. When the snow surface is colder than the underlying snow and there is a steep temperature gradient in the snowpack, snow will be warmer at the top of the crystal compared to the bottom of the overlying crystals. As a result, water molecules will release from the top of the crystal as the air is supersaturated with water vapor. The resulting crystals will therefore be rounded at the top and be faceted/have edges at the bottom (McClung and Schaerer, 2006).

2.2.1.3 Wet snow metamorphism

Wet snow metamorphism, also known as melt recrystallization, occurs when liquid water exists in the snowpack. Under these circumstances, there will be water in the pore spaces between snow grains. The process will, in this case, go faster, as water moves more quickly when it is in the liquid phase compared to the solid phase. The result is large melt forms and clusters of crystals.

2.3 Avalanche formation

Slab avalanches are considered to be the most destructive avalanche type. This type of avalanche has a significant damage potential by dragging large blocks of hard, compressed snow. Three factors are necessary to form a slab avalanche: a slab, a weak layer, and an inclination steep enough.

2.3.1 Weak layers

Weak layers can be a potential problem if buried by a slab. When focusing on weak layers and forests, three types are relevant: surface hoar, near-surface faceted crystals, and crusts (Gubler and Rychetnik, 1991). 40 % of weak layers are surface hoar, 25 % are faceted particles, and 15 % are depth hoar. (Fohn, 1992)

Kinetic growth close to the surface might lead to the formation of a weak layer. A persistent weak layer refers to a specific layer in the snowpack with remarkably lower shear strength than surrounding layers. If a weak layer collapses, it may cause an avalanche.

2.3.1.1 Surface hoar

Surface hoar are crystals that form on the snow surface. The sizes vary and can get up to several centimeters long, depending on the atmospheric conditions. It forms due to the deposition of water vapor on the snow surface during cold, clear nights with low wind speeds (1-3 m/s wind). A temperature inversion occurs at the surface due to increased outgoing longwave radiation on cold clear nights. As a result, the air just above the snow surface gets supercooled, and water vapor is deposited on the snow surface, forming surface hoar crystals. If subsequently, the crystals are covered with new snow, a collapse of the crystals may lead to an avalanche (Stössel et al., 2010).

However, studies on the surface energy balance in forests imply how the surface hoar formation will be altered. Forests can both enhance and limit this, depending on the density of the forest. As canopy, air, and snow surface temperatures are often in equilibrium in mature spruce forests; this will have a dampening effect on surface hoar formation. However, in openings where surrounding trees contribute to the shading of the snow surface, the surface hoar formation can be enhanced if the opening is large enough for outgoing radiation not to be reflected on the surface. This effect can be seen in the forest to open transitions (Gubler and Rychetnik, 1991). Forests also have the potential to lower wind speeds.

2.3.1.2 Faceted particles

Near-surface faceted crystals form as a result of constructive metamorphism due to temperature differences in the snowpack. A steep temperature gradient is a requirement for the crystals to form, and three main processes lead to these gradients.

Radiation recrystallization happens during high incoming longwave radiation. Most radiation is reflected because of high albedo on the surface, while some of the radiation heats up the subsurface, resulting in increased outgoing longwave radiation from the surface. The result is a strong temperature gradient between the cold surface and a warmer a few cm below.

The second process is called melt-layer recrystallization. It happens when the snow surface is heated because of rain or sun, followed by cold weather and precipitation. If the snow layer on top is relatively thin and the temperature is cold, a strong temperature gradient will appear close to the surface, and potentially faceted crystals will form.

The last process is called diurnal recrystallization. It happens when the surface gets very warm in the daytime due to, e.g., high incoming shortwave radiation, followed by rapid warming in the night Birkeland, 1998.

2.3.1.3 Depth hoar

Depth hoar is an extreme version of faceted particles that form in the snowpack's lower part. They usually form in early winter when the snowpack is relatively thin and air temperatures are low for extended periods. The low surface temperature creates a negative temperature gradient vertically in the snowpack, which again facilitates the growth of depth hoar. If air temperatures remain low for some time, the crystals grow large and persist as a weak layer in the snowpack (Akitaya, 1974).

2.3.2 Accumulation of a slab

Accumulation of a large enough and cohesive slab deposited on top of a weak layer during the same storm is an essential condition for slab avalanche formation. The slab can form either through a precipitation event or as a result of wind transport of snow (Gubler and Rychetnik, 1991).

2.4 Forest influence on snow processes

2.4.1 Forest snow interactions

Forest interacts with the snow cover in three ways; by changing the surface energy budget, holding back snow through interception, and anchoring the snowpack. The latter will not be explained here.

Forest changes the temperature equally, so forests do not significantly influence near-surface facets formation. However, dense forests can alter the continuity of the layer, so the weak layer is not persistent over a larger area. Local compaction of 20 % within an area of width between 1 to 2D (D - thickness of new snow layer) might lead to initial fracture. This compaction might come from intercepted snow falling on the snow surface (Gubler and Rychetnik, 1991). Weakness zones where initial fracturing can occur vary in size. The size depends on slab thickness and deformability. The weakness zone can be vast for hard slabs, such as wind slabs. Wind slabs do not form in forests.

2.4.2 Interception

Interception of snow by trees is another factor that alters the snowpack in forested areas. The amount of intercepted snow is dependent on forest properties and weather conditions, especially snowfall amount, forest density, and time since the snowfall. The effect applies to different parts of the world, both western Canada and Russia. This knowledge can help in estimating the distribution of snow in forests, based on leaf area, on a medium to large scale (Hedstrom and Pomeroy, 1998). Interception leads to alteration of the snowpack layers and modifies the distribution and accumulation rate of new snow during a storm (Gubler and Rychetnik, 1991).

The amount of snow that will get intercepted is higher when the branches are moderately loaded with snow compared to lightly and heavily loaded branches. This amount will increase until a certain point when the branch can not hold on to the snow, which results in a collapse and the snow falling to the ground (Gubler and Rychetnik, 1991; Hedstrom and Pomeroy, 1998). The intercepted snow is often more compact, resulting in holes of even more compacted snow underneath the trees. Recent studies have pointed out the need for more investigations of interception, as much of the previous interception modeling is based on a few field studies (Lundquist et al., 2021).

2.5 Snow-pack simulations using CROCUS and HPEval

For the modeling part of this thesis, the models CROCUS and HPEval have been used. The following two subsections give a brief explanation of the two models.

2.5.1 CROCUS

CROCUS was first developed by Brun et al. (1989). It is a one-dimensional multilayer physical snow scheme. It is used for simulating the movement of mass and energy in a snowpack as a function of energy and mass transfer between the snowpack and the atmosphere through radiation (longwave and shortwave), turbulent fluxes (sensible and latent heat), and ground heat fluxes. It simulates, e.g., the temperature, liquid water content, the density of the snow, type of snow grains, and the amount and hardness of the layers. CROCUS is integrated into the externalized surface module SURFEX, which extends the potential applications of CROCUS. The following input variables are needed in order to run the model; air temperature, specific humidity, wind speed, incoming radiation (shortwave and longwave), precipitation rate, and atmospheric pressure. (Vionnet et al., 2012).

2.5.2 HPEval

HPEval is a model that simulates sub-canopy shortwave radiation. The simulations are based on hemispherical images, i.e., pictures taken from below the canopy and up. The model considers the solar position to calculate the direct and diffuse shortwave radiation. These pictures are used to calculate the sky view fraction, which is then used to determine the amount of radiation that reaches the sub–canopy surface and how much is blocked by the canopy (Jonas et al., 2020).

CHAPTER 3

Methods

3.1 Study sites

Field work for this project was done in Nordmarka in Oslo, mainly in two different areas, Maridalen and Sørkedalen. Weather data for the modeling part were provided from the weather station at Bjørnholt, which is located 6 km east and North of the measuring sites at Sørkedalen and Maridalen, respectively (Figure 3.1). For both locations, open area measurements were done on agricultural fields to get the surface as even as possible. This was also desirable, however harder to achieve, in the forested site. Two main factors were weighted when picking the locations; closeness to parking and distance to infrastructure and ski tracks. This was taken into consideration to save time on traveling and avoid too much disturbance to the snow. This was successfully achieved in Sørkedalen. However, there were some disturbances from moose and other animals. In Maridalen, this was not completely achieved for the open area, but measuring sites were chosen depending on where the snow looked undisturbed. It was not wholly achieved, as a popular ski track crossed the field and potential disturbances from animals as well. The forested site, however, seemed for a large part undisturbed.

3.2 Field work

The fieldwork was conducted in winter 2022, from January 11 to February 23. The following is a description of the measurement methods used in this work.

3.2.1 Snow measurements

Coarse-resolution snow measurements were gathered in Nordmarka during the winter season 2021/22. Due to a lack of snow in the forest, measurements did not start before mid-January. On the first two field days in Sørkedalen (January 11 and 18), the snow pit profiles and depth measurements in the open were done at location 2 in Figure 3.1. To get measurements that were less influenced by the adjacent forest, the measurements were done at a point more in the middle of the field, at point 3.

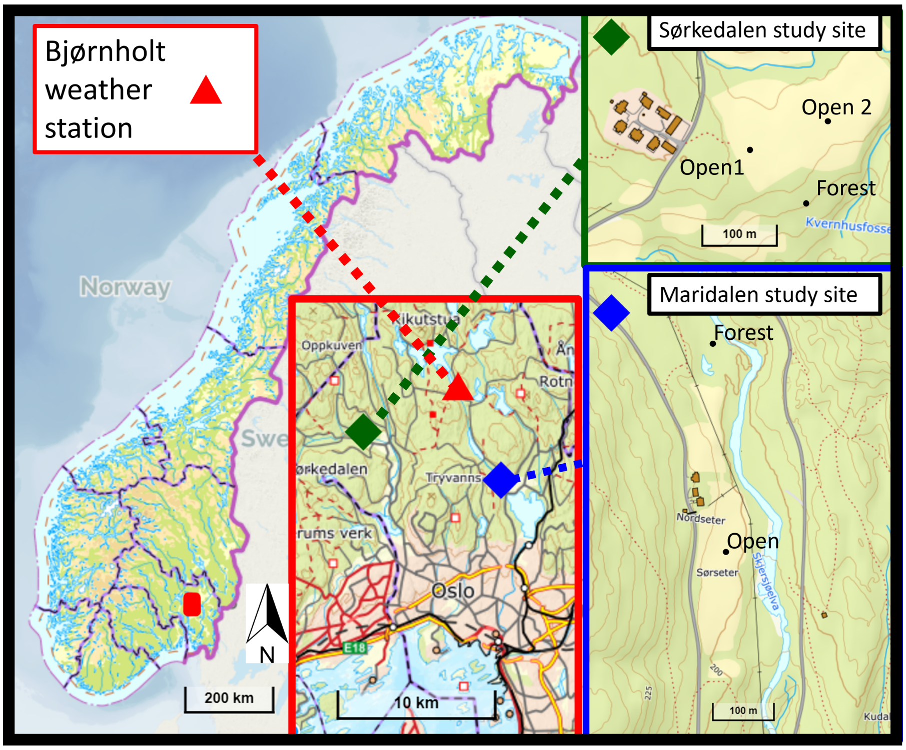

Figure 3.1: The figure shows an overview map of the area where field measurements were conducted, and the position of the forest and open sites. Bjørnholt weather station is where the data for the simulations were measured.

3.2.1.1 Snow pit

Snow pits were dug at each tree density location. Mainly one snow pit per day, and occasionally additional ones if necessary. In each snow pit, observations of grain type according to Fierz et al. (2009). The average grain size was also roughly estimated. Snow hardness was measured using the hand hardness test, and temperature and density were also measured.

3.2.1.2 Snow depth

The main goal of the snow depth measurements was to get enough measuring points so, in order to limit the effect of the uneven forest floor. In all sites, snow depth measurements were achieved by doing at least 30 measurements over an area of approximately 3 x 3 m. The measurements were spread out in a grid with at least 0.5 m between each point. This was easier to achieve in the open site than in the forested site, as trees could stand in the way of the measurements. That resulted in some points not being at the intended line, but the effect of this is assumed to be negligible. Snow depths were measured on the same square for each site on the measuring day. The equipment used was a 2.7 m BCA avalanche probe with a 1 cm resolution.

Table 3.1: Terms and resistance values for the method used in the hand hardness test. Modified from Fierz et al. (2009).

Term	**Hand test**			**Ram resistance (Swiss ramsonde) (N)**	
	Hand hardness index	**Object**	**Code**	**Range**	**Mean**
Very soft	1	fist	F	0–50	20
Soft	2	4 fingers	4F	50–175	100
Medium	3	1 finger	1F	175–390	250
Hard	4	pencil	P	390–715	500
Very hard	5	knife blade	K	715–1200	1000
Ice	6	ice	I	> 1200	> 1200

3.2.1.3 Shear strength

On days when a weak layer or interface was present in both forested and open areas, the shear strength of the weak layer was measured using a shear frame and a dynamometer. The shear frame is a metal frame with an area of 250 cm^2. The approach when measuring shear strength is to remove overlying snow down to about 40 mm above the weak layer that is being measured. Then, the shear frame is placed and pushed carefully down into the snow. As the measurements aim to investigate the shear strength of the weak layer, it is essential not to disturb the weak layer. This is achieved by pushing the frame gently down to about 5-10 mm above the weak layer. When the frame is placed, the dynamometer is hooked to the wire connected to the frame. The frame is then pulled until the weak layer collapses. It is also important to pull for approximately 1-second (Jamieson and Johnston, 2001). If the weak layer collapsed during frame placement, the following measurement would not be valid. In this scenario, the process had to be started from the beginning. For each site, 12 measurements were done to compensate for differences between measurements.

3.3 Modelling

The intent of using Crocus was to use the simulations as an analytical tool to look at the snow cover evolution throughout the winter. As opposed to the field measurements that only provide information about the snowpack at one point in time. The effect of the forest was then included by simulating four different forest scenarios. For this purpose, HPEval was used. The approach is now described.

All the necessary forcing–data for Crocus were provided from the operational met–Norway weather forecast using MEPS (*MetCoOp* n.d.). The data was provided as a time series with hourly resolution. HPEval (Jonas et al., 2019) was then used to create the different forest scenarios. The scenarios were based on four hemispherical images, taken at different locations related to forest openings; at the south end (picture A in Figure 3.2), in mid–opening (B in Figure 3.2), in the northwest end of the opening (C in Figure 3.2, and in mid–forest (D in Figure 3.2). The photos were taken in Södankyla in Finland and provided through the work of Mazzotti et al. (2020).

Using HPEval with the hemispherical pictures as input, four different forcing datasets were created by modifying the radiation incoming longwave and shortwave radiation.

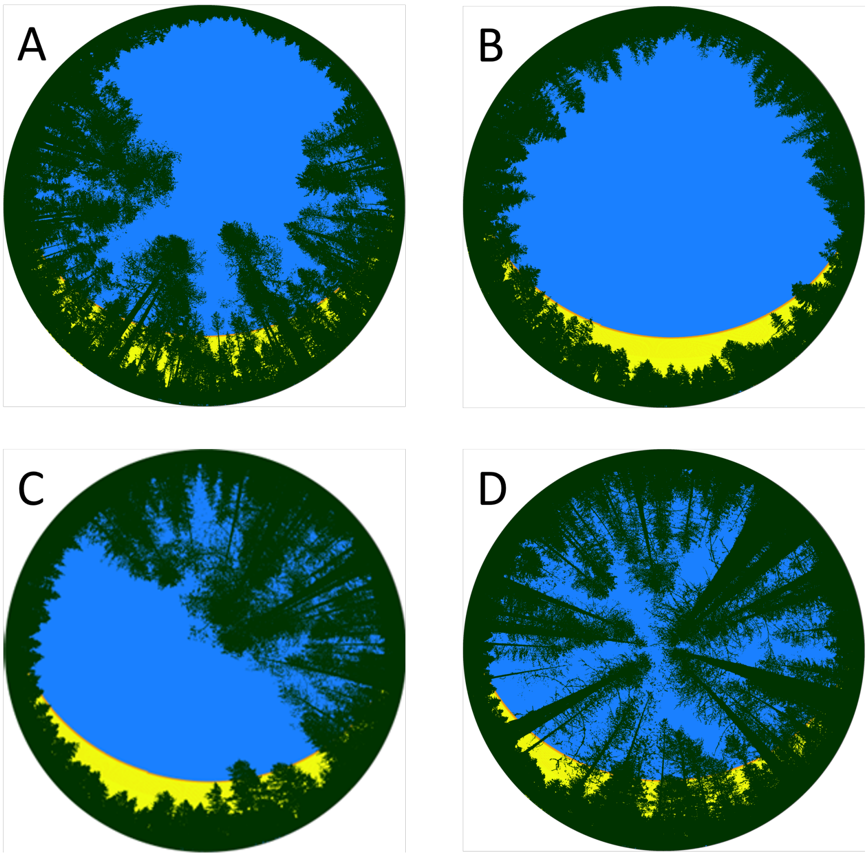

Figure 3.2: Hemispherical photos used for the simulation of different forest scenarios, provided from Mazzotti et al. (2020). The photos are taken in different areas related to forest openings. Picture A is taken at the southwest end of an opening. Picture B is taken in the middle of an opening. Picture C is taken at the northeastern end of an opening. Picture D is taken in the middle of the forest.

CHAPTER 4

Results

The result chapter starts by describing the snow season in Nordmarka winter 2021–2022. The following part is divided into two sections: field data and simulations. The field data section is divided into two subsections, where the first subsection shows measurements of snow temperature, snow depth, shear strength, and hardness. The second subsection contains pictures and descriptions of some phenomena that were observed but not measured. The simulations section contains selected simulations of these measured variables.

4.1 Winter 2021–2022

Figure 4.1 shows the measured snow depth, precipitation, and temperature at Bjørnholt in winter 2021–2022. Snow first started to settle at the end of November 2021. The average temperature was around $-10°C$ in the first week of December when this snowfall occurred. The first snowfall was followed by a temperature increase, which resulted in a decrease in snow depth. In the last part of December, temperatures were stable below zero, while the snow depth remained low. At the beginning of January 2022, there was a significant decrease in temperature, followed by an increase in snow depth and temperature. The next event worth noting is a rapid ten cm increase in snow depth over a few days at the end of January, and ten days later, snow depth decreased by 10 cm in two days. Then, the snow depth increased again, with 20 cm in two days. This was also when the highest daily precipitation was measured during the winter, 43 mm on February 15. Snow depth was at its peak on February 23, at 57 cm.

4.2 Field data

4.2.1 Measurements

In the following subsections, the results from snow depth measurements and snow profiles are presented.

4.2.1.1 Snow depth

Snow depth measured in the field is shown in Figure4.2. The highest values are measured in the open in Maridalen. Snow depths are always higher in the

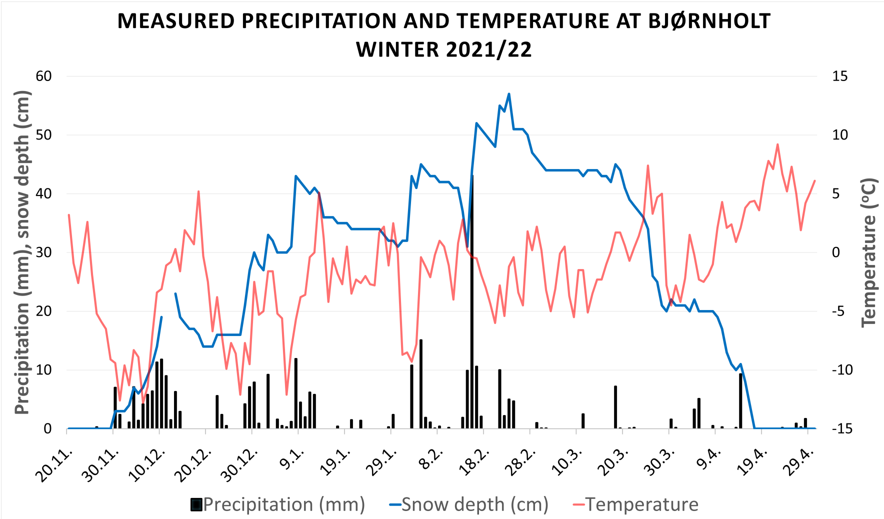

Figure 4.1: Measured snow depth, temperature and precipitation from Bjørnholt weather station in Oslo, Norway in the winter 2021–2022.

open compared to forests. The forest in Sørkedalen shows generally higher snow depth values compared to Maridalen.

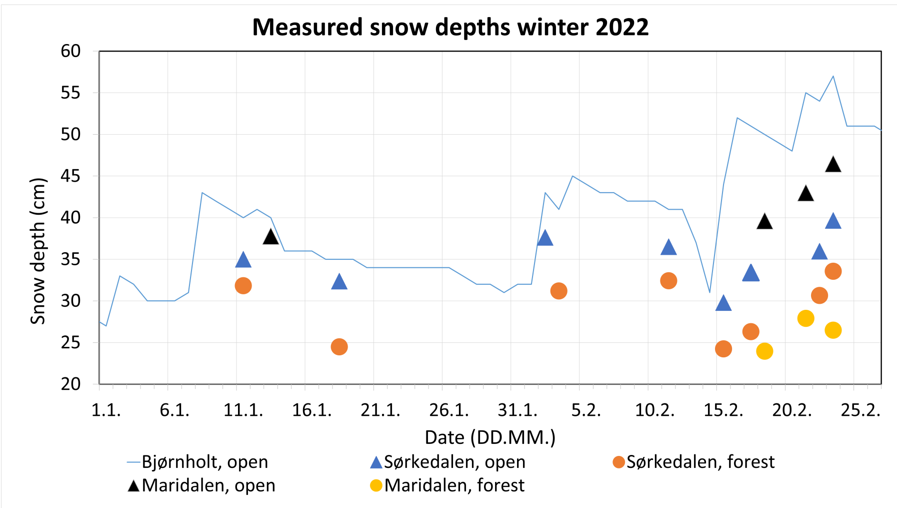

Figure 4.2: Plot of mean measured snowdepth from field and weather data from Bjørnholt. The standard deviations are shown in table4.1. Snow depth data from Bjørnholt is provided through *Norsk Klimaservicesenter* n.d.

4.2.1.2 Snow pit profiles

This section will give a brief explanation of the characteristics of the snow cover through the snow pit profiles. The focus will be on grain type and -size, temperature, and hardness, and not so much on snow depth.

On January 18 in Sørkedalen (Figure4.3, 4.4), nine snow layers were registered in the open and four in the forest. The open-pit were dug at location 1 and the forest pit at location 2 (Figure3.1). Depth hoar was observed at the bottom in both snow pits. Rounded grains were observed in all layers in the forest pit and only in two layers in the open pit. Two ice layers were observed in the open and one in the forest. Surface hoar was observed in the open pit, 6 cm below the snow surface. Some faceted grains were observed in the open, from 12 cm above the ground and down.

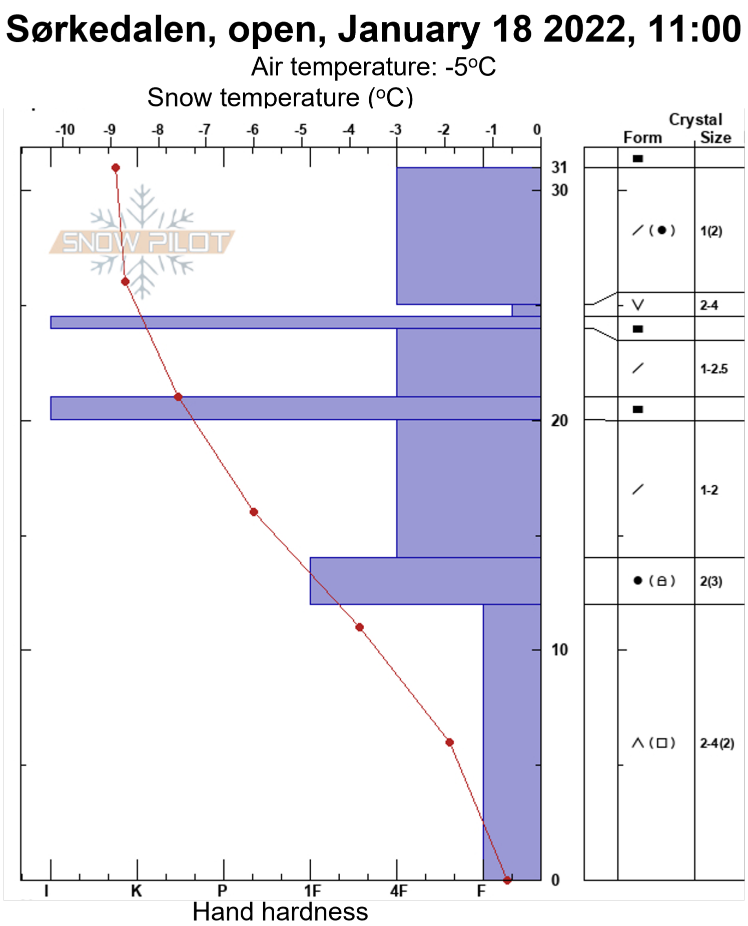

Figure 4.3: Snow profile from the open site in Sørkedalen on January 18 2022.

On February 2 and 3 (Figure 4.5 and 4.6), the open pit was quite similar to how it was on January 18. Some of the layers in the open had more faceted and rounded grains, and the layer of surface hoar was not observed. An extra ice layer was observed in the forest pit. There were faceted grains in the layers below each ice layer in the forest pit. The snow surface was 11 °C colder than the air temperature in the open and equal in the forest.

On February 11, the tendency was similar to February 2 and 3, with more changes in layer properties in the forest compared to open. In the open pit

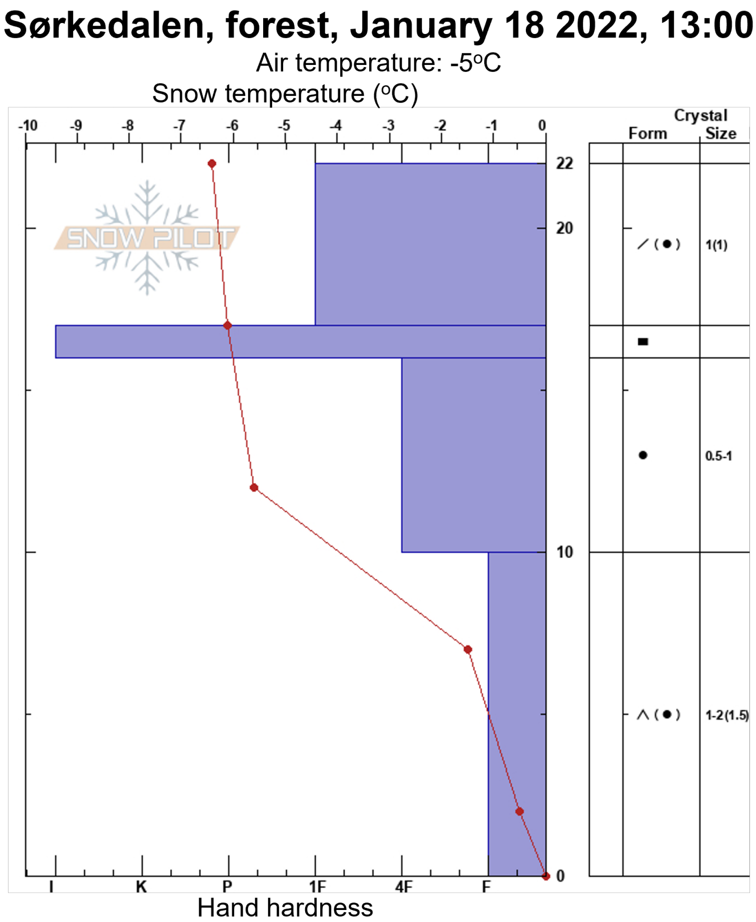

Figure 4.4: Snow profile from January 18 2022 in the forest in Sørkedalen

(Figure 4.7), some of the layers decreased in thickness, and a new layer was observed under the lowest ice layer. This new layer contained clustered grains with some faceted crystals. Surface hoar was observed on the surface. In the forest pit (Figure 4.8, there was a porous, uneven melt-freeze crust on the top. Faceted grains were observed. There was an increase in hardness at the bottom of the snowpack, and large (15 mm in diameter) clustered grains were observed at this point. The snow surface was 10 °C colder than the air temperature in the open and 3 °C colder in the forest.

After February 11, many snowpack properties changed, which resulted in a different snowpack on February 15. The snow mainly consisted of clustered melt forms in the open pit (Figure 4.9), only interrupted by two ice layers and a thin layer of decomposed, fragmented precipitation particles on top. The hardness of the bottom — 27 cm layer was lower than fist, and from 27 cm and up, hardness increased to pen hardness just below the surface. The forest snowpack (Figure 4.10) had three layers; the lowest layer had a hardness of 4f and was 17 cm thick. Above this was an ice layer with 2 cm thickness with

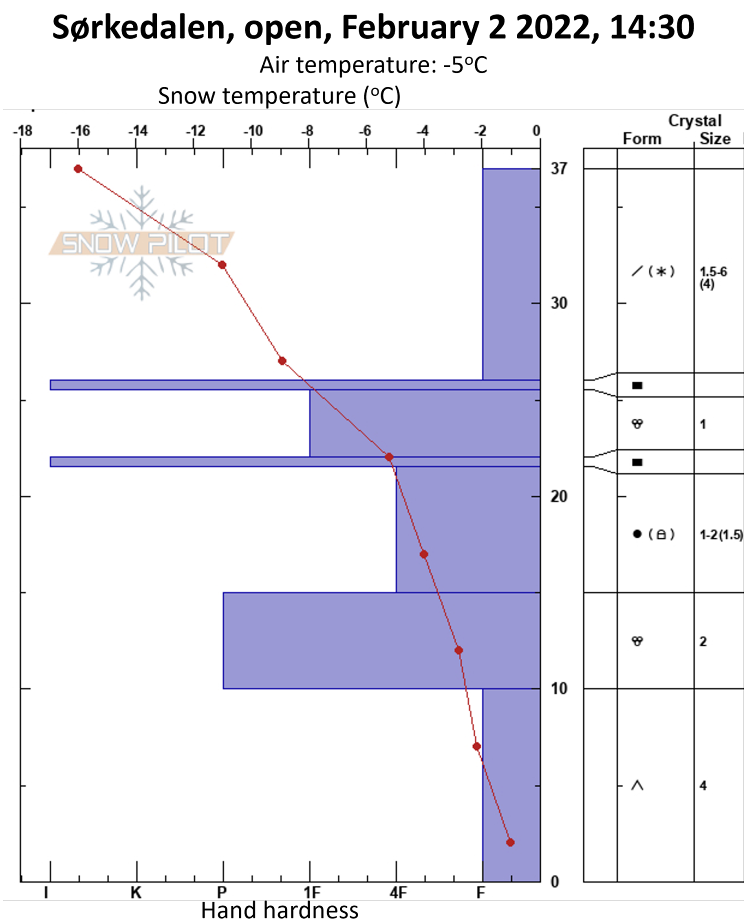

Figure 4.5: Snow profile from the open site in Sørkedalen on February 2 2022

decomposed particles on top. The temperature was 0 in both pits, and the only exception was at the surface in the open, where it was $-1\,°C$.

The next day of snow pit measurements was February 17. The hardness had increased from 25 cm up in the snowpack and down in the open pit (Figure 4.11). The top layer consisted of decomposed particles, and a layer of faceted crystals was underneath. The hardness in the forest pit (Figure 4.12) decreased in the layer 10 - 19 cm above the ground. There were observed faceted crystals in this layer, and over this was an ice layer. On top of that were decomposed particles. The temperature was zero in the whole forest pit. In the open pit, temperatures were zero up to 19 cm above the ground and then decreased gradually to $-2\,°C$ at the surface. In both locations, the air temperature was $1.6\,°C$.

On February 22, further increase in hardness in the layer 20 cm above ground and down in forest and open was observed (Figure 4.14 and 4.13). The temperature started to decrease from the ground in both pits. More faceted grains were

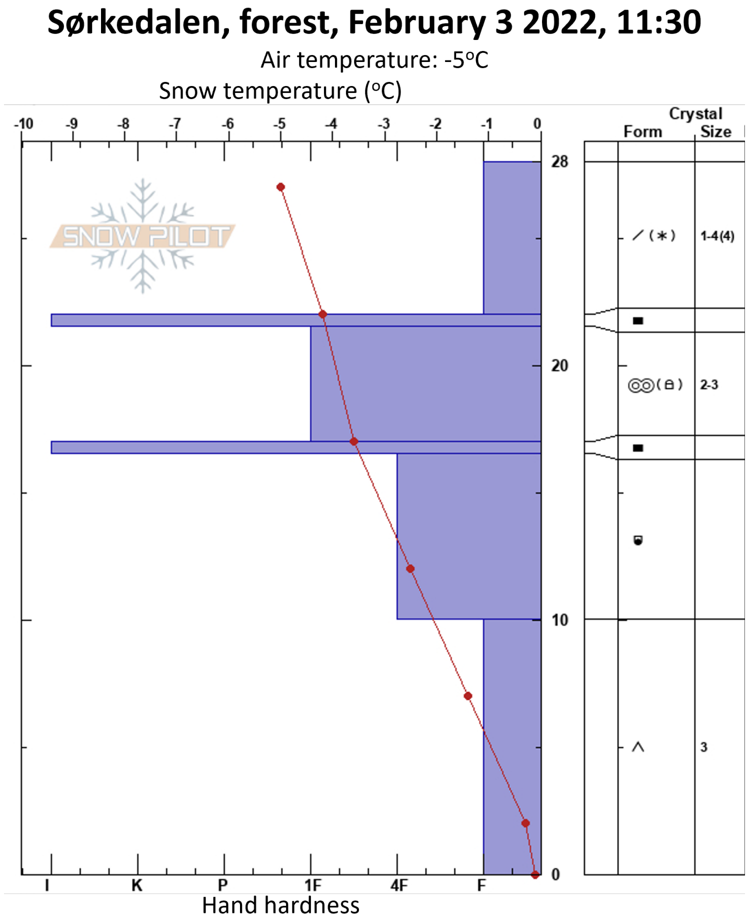

Figure 4.6: Snow profile from the forest site in Sørkedalen on February 3 2022.

observed in both forest and open, at 20 and 30 cm above the ground in open and at 20 cm above ground in forest. In the forest, the faceted grains were on top of an ice layer. Surface hoar were observed in the top layer in the open pit.

4.2.1.3 Temperature gradients

Temperature gradients higher than 40 °C/m were observed on several occasions during the field campaign. Table 4.5 show selected measurements of temperature gradients when the lowest temperature in the points where the gradient was measured was above or equal to -6 °C. The strongest observed temperature gradient was 100 °C/m and was measured on February 22 in the open birch forest at the site in Sørkedalen. On the same day, the weakest observed temperature gradient in the open site was 43 °C/m. Other high values is 82 °C/m in Sørkedalen open field on January 18, with the weakest in the forest at 44 °C/m, a high gradient throughout on February 18 in Maridalen open site and a high observed gradient in areas with different vegetation on February 11.

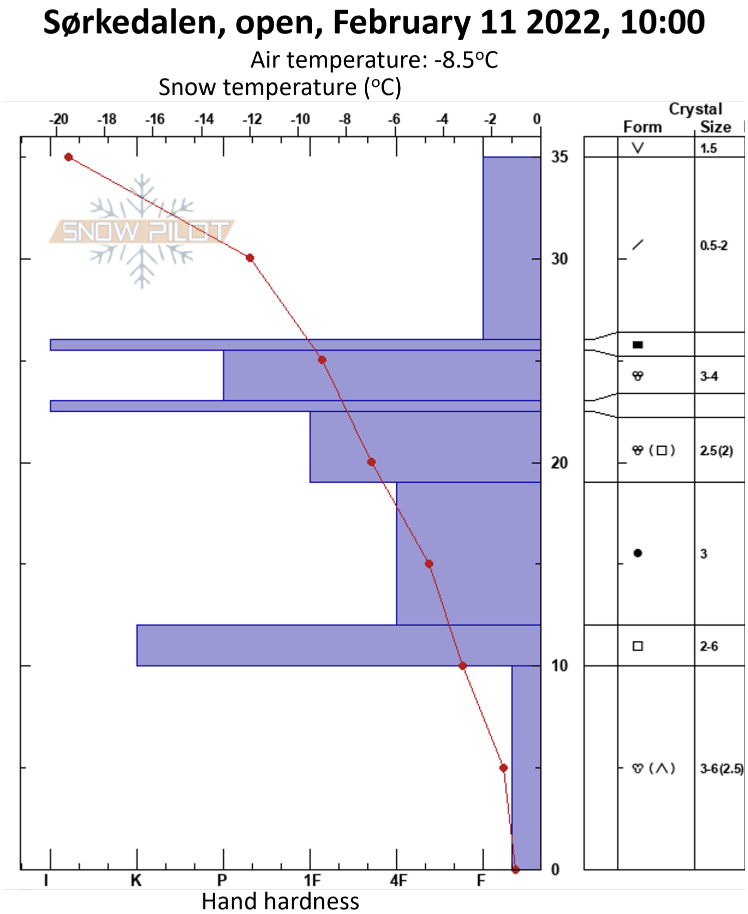

Figure 4.7: Snow profile from the open site in Sørkedalen on February 11 2022.

4.2.1.4 Shear strength

Table 4.6 show all the shear strength that was measured during the fieldwork. On all days except February 2 and 3, there are higher shear strength in the open compared to the forest. The largest difference between shear strengths was measured in Maridalen on February 17, when shear strength was 2328 Pa in the open, and 1100 Pa in the forest.

4.2.2 Observations

4.2.2.1 Surface hoar

Surface hoar was observed on seven out of twelve field days. On January 13, February 11 and 18, it was on the surface, on the remaining days it was buried by a layer of newly fallen snow. The surface hoar found on January 13 in the Maridalen site were needle shaped and 4 mm long. In Sørkedalen , February 11 and 18, the crystals had a triangular shape. Observations from February 11 show spatial differences in surface hoar occurrence and size within the open

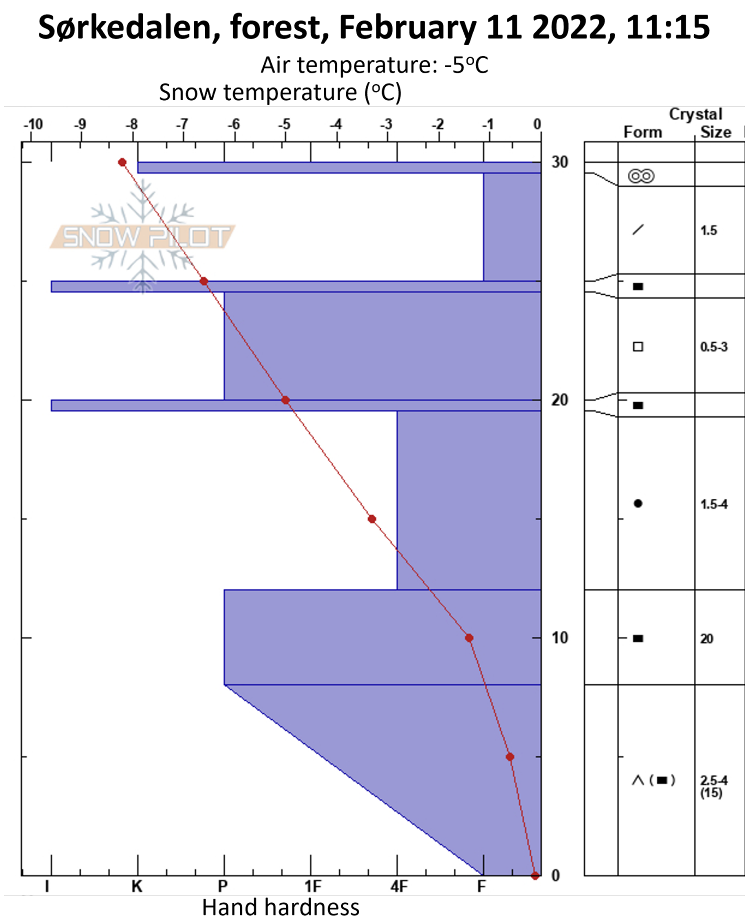

Figure 4.8: Snow profile from the forest site in Sørkedalen on February 11 2022.

site. In the vicinity of the forest edge, surface hoar crystals 14 mm long were observed, while in in the center of the field the average length was around 2 mm.

4.2.2.2 Wind transported snow

On February 22, some features that might indicate wind transport was observed in the open site. First of all, wavy formations on the snow surface were observed. Where the snow seemed undisturbed, the snow surface was uneven. In addition, footprints in the snow from measurements four days earlier was on this day almost fully filled up with snow again. From the weather data, we see that there was less precipitation registered these four days. Another observation was that the new snow was very cohesive. When digging in the snow, the top layer held together well.

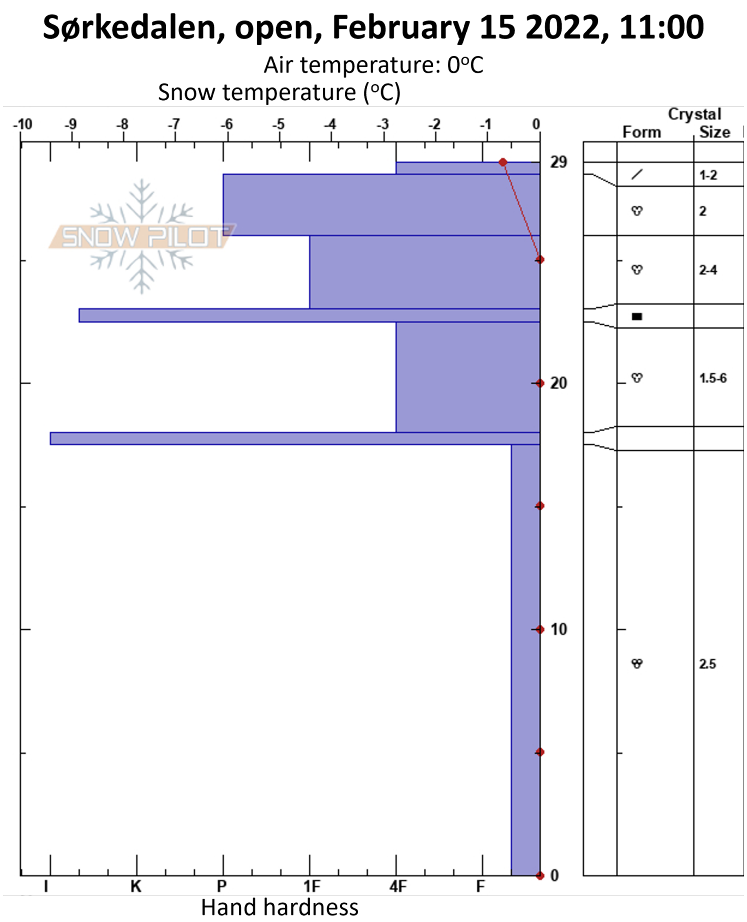

Figure 4.9: Snow profile from the open site in Sørkedalen on February 15 2022.

4.2.2.3 Interception

Snow was falling from the trees during measurements one day. It was falling in quite big lumps. They were approximately 5-10 cm in diameter. They fell to the ground after gusts of wind.

4.3 Simulations

This section will show simulations of the parameters that were measured during the fieldwork, such as snow temperature, depth, hardness, shear strength etc. To compare simulations with measurements, the focus for some of the simulations will be on days where

4.3.1 Snow depth

Figure4.16 show the simulated snow depth for the different forest regimes. The numbers correspond to the hemispherical images from HPEval, shown in

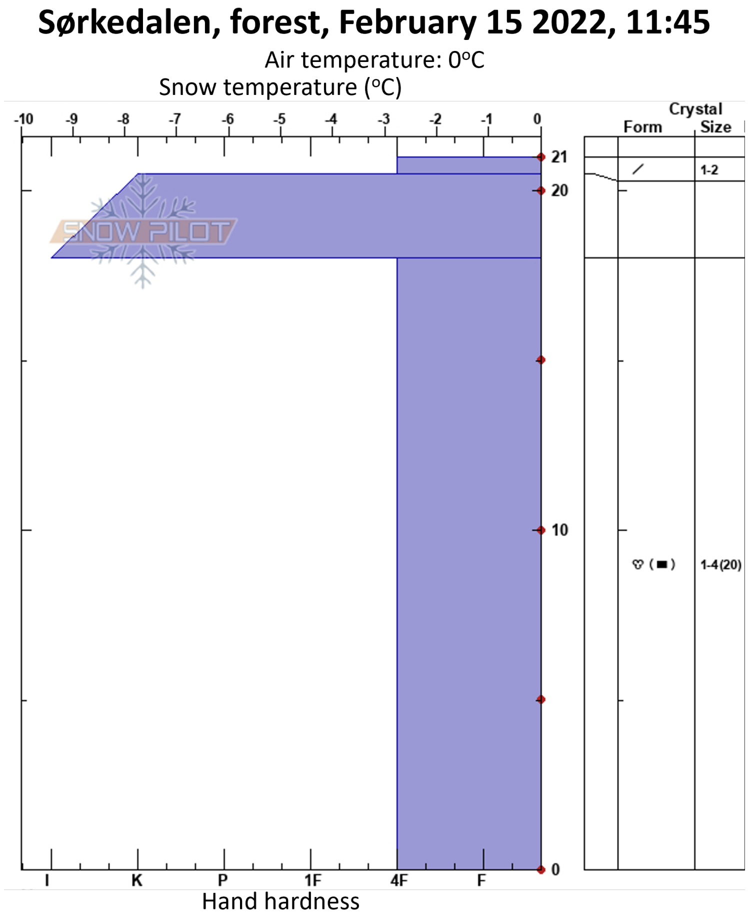

Figure 4.10: Snow profile from the forest site in Sørkedalen on February 15 2022.

Figure3.2. All forest scenarios follow a similar pattern until the main ablation season starts. This pattern will therefore be described as one scenario until mid-March when snow depths start to develop in different ways depending on forest scenario.

Snowpack starts to develop in late-November 2021. It starts with a small snow fall of a few cm's, before a larger one which increases snow depth up to 8 cm. It remains at this height for some days before a small increase. Following is a steady increase for one week where snow depth increase from 10 to 25 cm. Then a small decrease to 20 cm. At the end of December–beginning of January, there are three increases in snow depth over one week, each with similar duration and magnitude. The resulting snow depth is 30 cm. It is then stable for some days before a new increase of around 15 cm, and a snow depth of 45 cm. Then, a three week period with a slight decrease. This is the first time where some difference between the scenarios can be observed. Forest snow depth shows the largest decrease, southwest and northeast equal and second-largest decrease

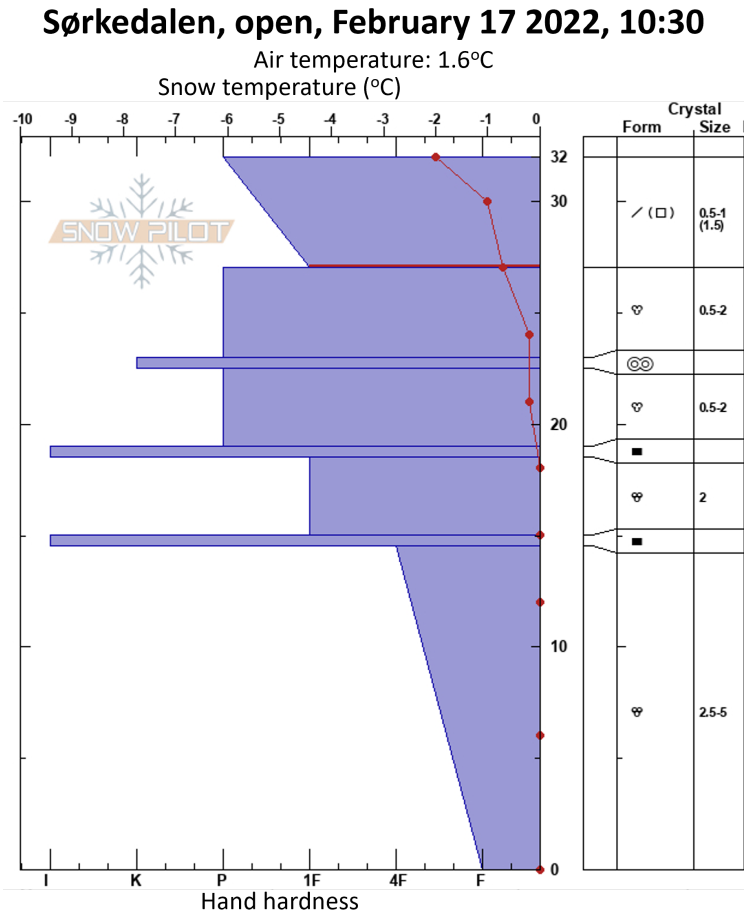

Figure 4.11: Snow profile from the open site in Sørkedalen on February 17 2022.

and open show the smallest decrease. This difference remains. There is a new snow fall at the beginning of February, which result in a snow depth increase from 35 to 45 cm, followed by no change for 10 days. On February 12, there is a small decrease (2 cm) followed by a large increase (30 cm). This is the point where snow depth is at the highest. After this, snow depth decreases to 60 cm, followed by a 5 cm increase. It then remains at this depth for around three weeks. In mid-March, snow depth starts to decrease in all scenarios. The decrease is largest in the northeast, where it goes from 65 to 25 cm in two weeks. Scenario forest and open have the same decrease for 10 days. The last 5 days, snow depth in forest scenario decreases more than open, resulting in a decrease from 65 to 45 cm and 40 cm for open and forest, respectively. southwest has the smallest decrease, from 65 to 60 cm in the same period.

4.3.2 Snow temperature

Figure4.17 shows the simulated snow temperatures. The temperature seems to change in more or less the same manner for all the forest scenarios, at least in

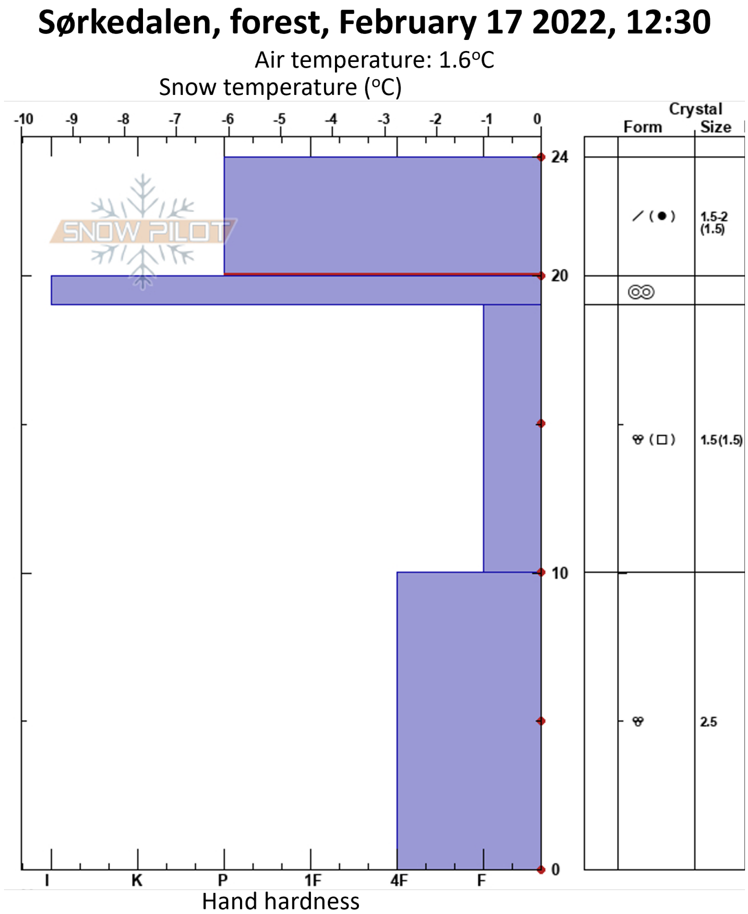

Figure 4.12: Snow profiles from the forest site in Sørkedalen on February 17 2022.

the accumulation season. The difference is in the magnitude of changes. For that case, the general trend is that open had the coldest, followed by northeast and southwest which were relatively equal and forest which had the warmest snow temperatures. This applies for nearly all temperature changes, so I will briefly explain the changes without commenting on the differences between forest sites. In addition, temperatures at the bottom of the snowpack are often equal, or close, to zero. The description will therefore be focused on the upper layers of the snowpack. If nothing else is specified, the change applies to the upper 10-15 cm of the snowpack.

When snow first started to accumulate in late November 2021, the surface snow temperature was generally low. Snow depth and temperature started to gradually increase around December 10, continuing until December 14. After this, some fluctuations in snow temperature at the surface can be seen, before it remains relatively cold for 1 week (December 23–29). This is followed by an increase in temperature (January 2–4), before it cools again. The temperature

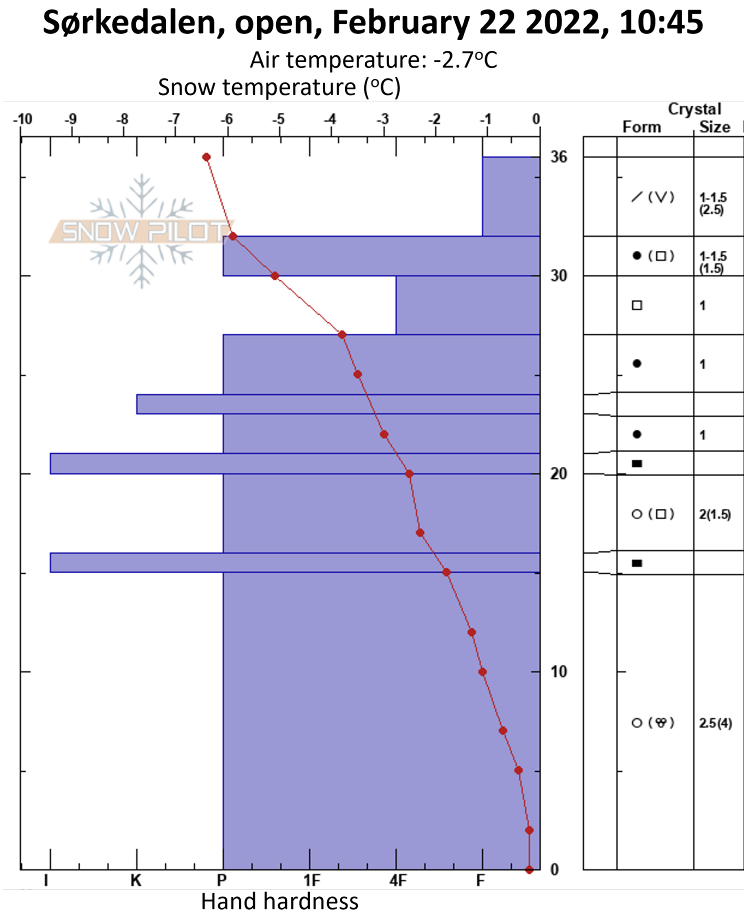

Figure 4.13: Snow profiles from the open site in Sørkedalen on February 22 2022.

then rises as snow depth increases as well. Then, a period of around one month (January 12–February 4) with fluctuating temperatures, with temperature changes on a daily basis. On February 4, there is a temperature increase which is observed to have an effect for a few days. ..and snow at 15 cm below the surface remain warm for a few days while the surface is cooled again.

After some days of cooling, the entire snowpack temperature rapidly increase. The increase is visible throughout the whole snowpack, all though the largest differences can be seen close to the surface. The snowpack stays warm until February 17. After this, there is a temperature decrease at the surface which propagate deeper into the snowpack. The decrease continue to advance further into the snowpack, although held back by two heating events, one on February 24 and one February 28. At the same time, there are daily fluctuations in surface temperature, with warmer during the day and colder during the night. This goes on until March 16, when another heating event happens. The snowpack temperature increases to around 0 °C. Then, the temperature start to fluctuate

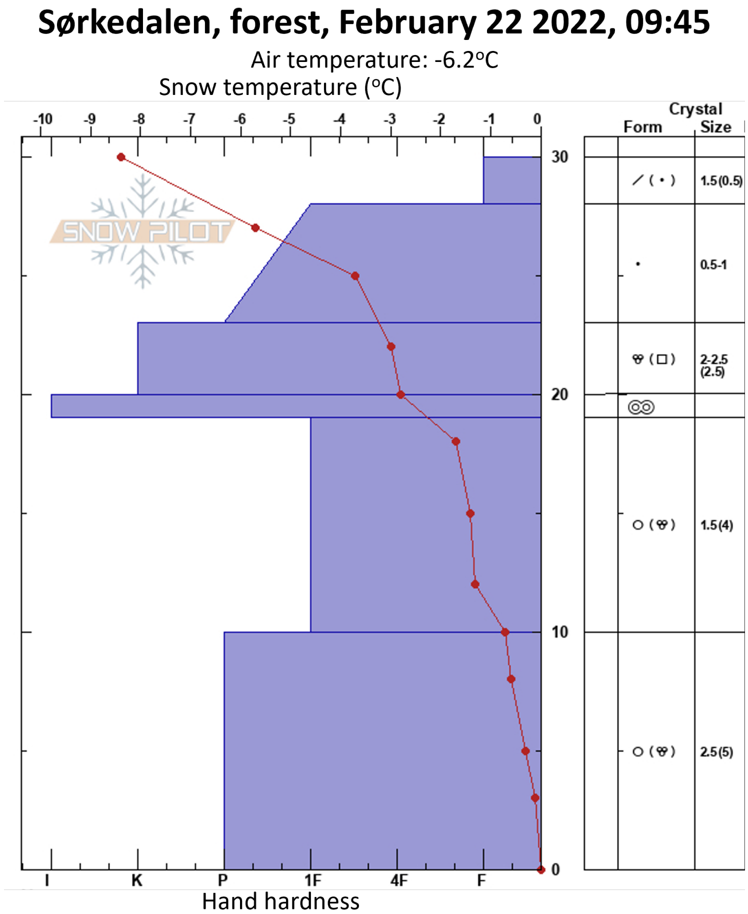

Figure 4.14: Snow profiles from the forest site in Sørkedalen on February 22 2022.

daily. At this point, the southwest scenario stands out with noticeably colder temperatures.

This figure shows simulated temperature profiles on days of fieldwork are shown in Figure4.18. For each day, the temperature profile from the open scenario is shown. In the first five plots (January 11 - February 11), the temperature decreases from the first step up from the ground in to the snowpack. The last five simulations from February 15–21, show a similar trend which is different compared to the previous. For large parts of the snowpacks, the temperature is 0 °C. On February 15th, it shows 0 °C for the whole snowpack. For the remaining days, snow temperature is at 0 °C up to a point before it decreases further. This point moves further down as time goes, starting at 13 cm below the surface on February 17 and ending up at 25 cm below on February 21.

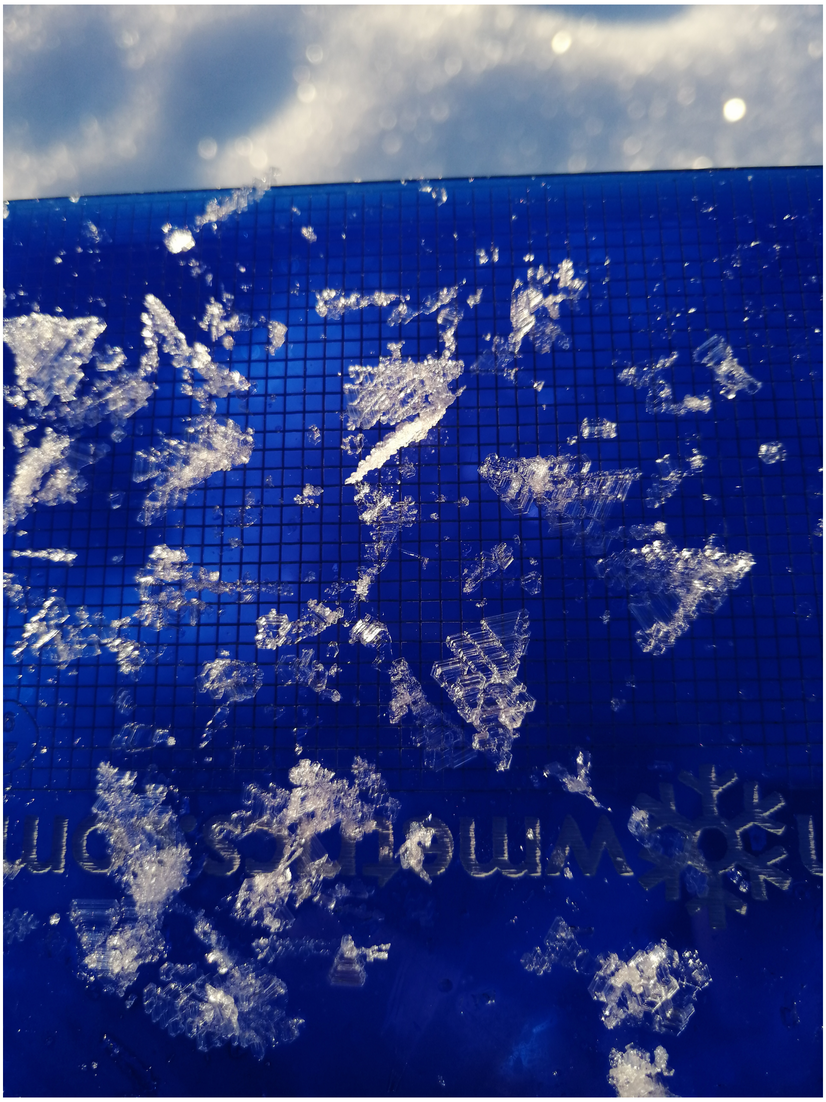

Figure 4.15: Surface hoar observed on the surface in the southwestern part of the open field on February 11. The squares on the crystal card are 2 mm wide.

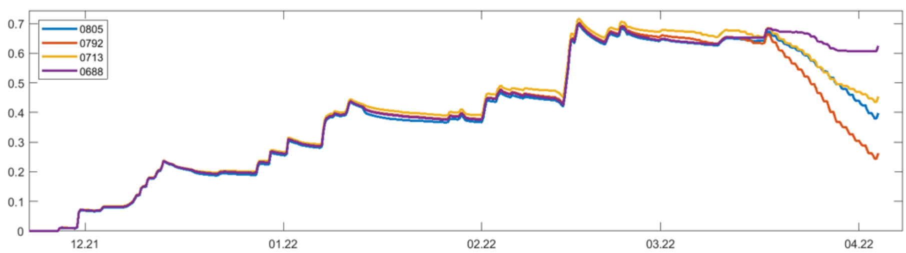

Figure 4.16: Simulated snow depth in all scenarios. 0805 — forest scenario, 0792 — northeast in opening, 0713 — middle of opening, 0688 — southwest in opening

Table 4.1: The table shows mean snow depths (H_s) and standard deviations of snow depth measurements in Sørkedalen (Srk) and Maridalen (Mrd).

Day (mm.dd.)	**Site**	**Mean H_s (cm)**		**Standard deviation**	
		Open	**Forest**	**Open**	**Forest**
01.11.	Srk	35	31.8	0.52	2.20
01.13.	Mrd	37.7	n/a	0.4	n/a
01.18.	Srk	32.4	24.5	0.8	2.2
02.02.	Srk	37.5	n/a	1.7	n/a
02.03.	Srk	n/a	31.4	n/a	4.2
02.11.	Srk	36.5	32.4	1.6	2.5
02.15.	Srk	29.6	24.0	1.3	2.3
02.17.	Srk	33.5	26.3	1.7	2.7
02.18	Mrd	39.5	24.1	1.2	2.3
02.21.	Mrd	42.8	28.2	1.6	2.8
02.22.	Srk	35.9	30.1	2.1	3.1
02.23.	Mrd	46.5	27.2	1.5	3.1
02.23.	Srk	39.7	33.6	1.5	2.4

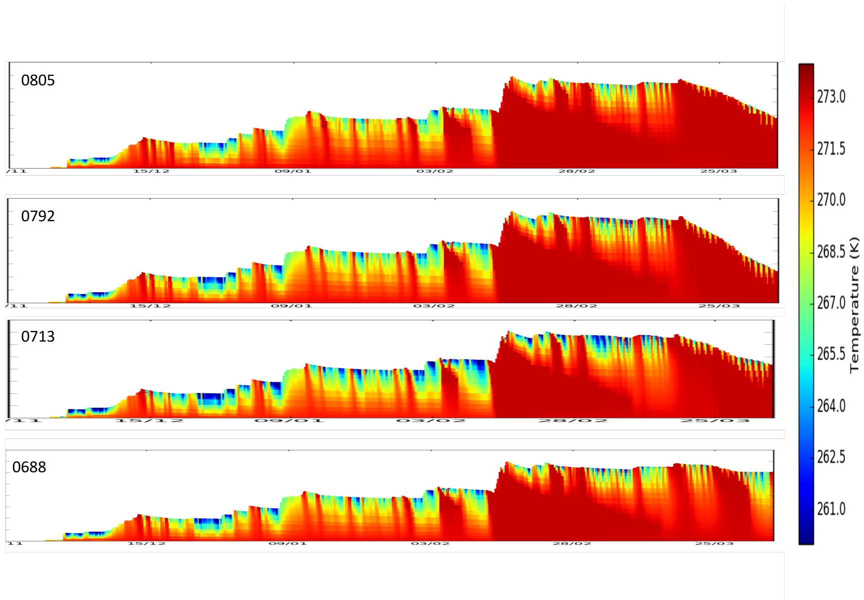

Figure 4.17: Simulated snow temperature. 0805 — forest scenario, 0792 — northeast in opening, 0713 — middle of opening, 0688 — southwest in opening

Table 4.2: The table shows snow depth (H_s), potential weak layers (SH — surface hoar, FC — faceted crystals, DH — depth hoar) and their position in cm above ground in the forest (F) and open (O). The heights are in parentheses if the grain type was registered as a secondary layer. A dash means that the grain type was not present. n/a means that no measurements were conducted on that site on that day. Srk — Sørkedalen and Mrd — Maridalen.

Day (mm.dd.)	**Site**	**H_s(cm)** F	O	**SH (cm)** O	**FC (cm)** F	O	**DH (cm)** F	O
01.11.	Srk	28	35	28	-	-	0-10	0-14
01.13	Mrd	n/a	37	29, 37	n/a	-	n/a	0-13
01.18.	Srk	22	31	24	-	(12-14)	0-10	0-12
02.02./ 02.03.	Srk	28	37	-	10-17 (17.5-22)	(15-22)	0-10	0-10
02.11.	Srk	30	35	35	20-24.5	10-12 (19-22)	0-13	(0-10)
02.15.	Srk	21	29	-	-	-	-	-
02.17.	Srk	24	32	-	(10-19)	27	-	-
02.18.	Mrd	24	38	38	(10-15) (15.5-19)	32	-	-
02.21.	Mrd	25	42	38	-	34 (23-28)	-	-
02.22.	Srk	30	36	32	(20-23)	27-30 (16-20)	-	-

4.3.3 Snow hardness

Figure4.19 show the simulated hardness in all forest scenarios with modified SW- and LW-radiation, showing one plot per forest scenario. With some small exceptions, the general trend in hardness evolution is similar for all forest scenarios from the beginning of winter until February 16. Although the simulated hardness have similar values after February 16 as well, it was deemed useful to explain the differences. This section will therefore explain the general trend of how the hardness of the snow layers evolve throughout the winter from start until mid–February, and then the specific evolution of hardness from mid February until the snow has melted.

In all forest scenarios, the first few snow falls results in a snowpack of equal hardness (1 daN). This is followed by a hardness increase at the surface. This happens four times. The fourth time, hardness increases in a larger part of the snowpack. February 13, snowpack hardness decreases so that it is equal in entire snowpack. This hardness similarity lasts until February 15, when hardness at the surface and close to the ground starts to increase. This increase starts to spread out into the snowpack, resulting in a snowpack which is softer at the surface and becomes gradually harder towards the ground, for all forest scenarios except northeast, where a thin layer of slightly lower hardness can be observed at 12 cm above ground.

This transformation into a snowpack with hardness increasing with depth from snow surface, happens in different speeds depending on the forest scenario. it

Table 4.3: The table shows the average hardness and number of layers on each field day.

Day	**R a (ram resistance)**		**Layers**		**Ice layers**	
(mm.dd.)	Forest	Open	Forest	Open	Forest	Open
01.11.	103	119	4	6	1	2
01.13	n/a	162	n/a	8	n/a	3
01.18.	148	131	4	8	1	2
02.02./ 02.03.	118	153	6	7	2	2
02.11.	296	183	8	8	2	3
02.15.	219	140	3	7	1	2
02.17.	183	283	4	8	1	3
02.18.	278	376	6	10	2	4
02.21.	741	461	4	12	2	4
02.22.	446	466	6	10	1	3

Table 4.4: The table shows Δ T between snow surface and air, between snow surface and bottom of snowpack, and the mean temperature in the snowpack.

Day	$T_a - T_{ss}$		$T_g - T_{ss}$		$\mathbf{T}_{average}$	
(mm.dd.)	**Open**	**Forest**	**Open**	**Forest**	**Open**	**Forest**
01.13	5.7	n/a	3.7	n/a	-1.8	n/a
01.18.	3.4	0.9	8.2	5.9	-5.4	-4.0
02.02.	6.7	n/a	15	n/a	-6.1	n/a
02.03.	n/a	-0.4	n/a	4.9	n/a	-2.4
02.11.	11	4.2	18	8.1	-7.2	-3.6
02.15.	0.7	0	0.7	0	-0.1	0
02.17.	3.6	1.1	2	0.4	-0.6	0.1
02.18.	4.5	-2.3	7.5	0.7	-4.3	-1.0
02.21.	0.5	0.1	1.3	0.7	-1.2	-0.5
02.22.	2.2	3.7	8.4	6.2	-3.5	-4.1

Table 4.5: Measured temperature gradients above 40 °C/m, with site, vegetation type and date. Temperature profiles can be found in Appendix

Site	**Terrain**	**Date**	**Gradient (°C/m)**
Sørkedalen	*Open*	2022 – 01 – 18	44
Sørkedalen	*Birch*	2022 – 01 – 18	82
Movatn	*Spruce*	2022 – 02 – 22	55
Movatn	*Open*	2022 – 02 – 22	36
Maridalen	*Open*	2022 – 02 – 18	57
Maridalen	*Open*	2022 – 02 – 18	64
Maridalen	*Open*	2022 – 02 – 18	36
Sørkedalen	*Birch*	2022 – 02 – 22	100
Sørkedalen	*Birch*	2022 – 02 – 22	44
Sørkedalen	*Open*	2022 – 02 – 22	40
Sørkedalen	*Open*	2022 – 02 – 22	43

Table 4.6: Table showing the measured shear strength in open(SS_o) and in the forest(SS_f), with the corresponding standard deviations on each day (SD_o and SD_f). Values are given in Pascal (Pa).

Site	***Date***	$SS_o(Pa)$	SD_o	$SS_f(Pa)$	SD_o
Sørkedalen	$2022-02-02$	184	24	–	–
Sørkedalen	$2022-02-03$	–	–	192	36
Maridalen	$2022-02-17$	2328	276	1100	360
Sørkedalen	$2022-02-18$	1480	296	1160	252
Sørkedalen	$2022-02-21$	1000	36	384	108

happens fastest in open, second in southwest and forest and slowest in northeast. after

4.3.4 Grain type

Figure4.20 show the simulated grain type for all forest scenarios. The following paragraph is a general description of the main features in the grain type evolution in the four forest scenarios. The difference between the scenarios are discussed in the next chapter.

The simulations of grain types show a similar series of events when snow depth increases. First, precipitation particles falls at the top. At the surface and 1-2 cm down, the grains turn into melt forms. These layers are persistent for some weeks, however they change character and end up containing more faceted crystals when covered by a new snow layer. Underlying snow gradually becomes decomposed and rounded, and eventually turn into faceted crystals and depth

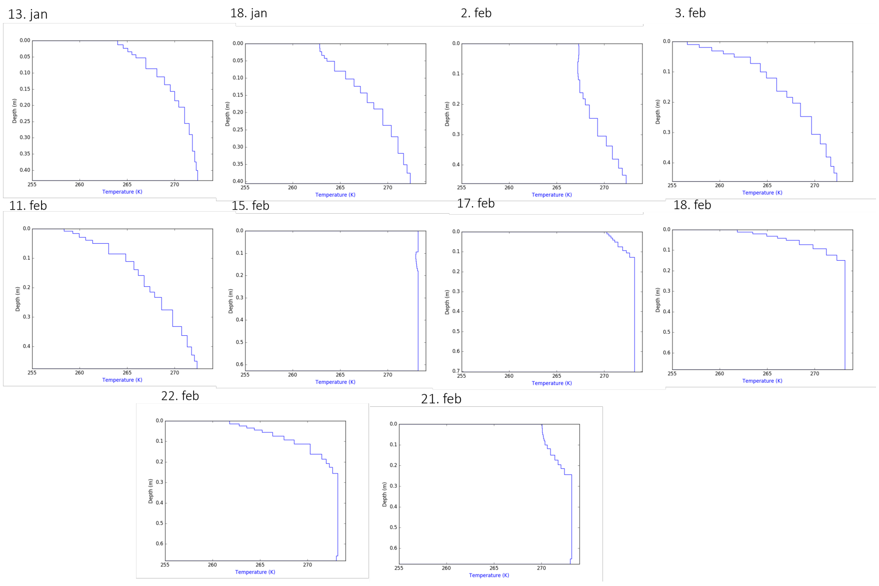

Figure 4.18: Simulated temperature profiles.

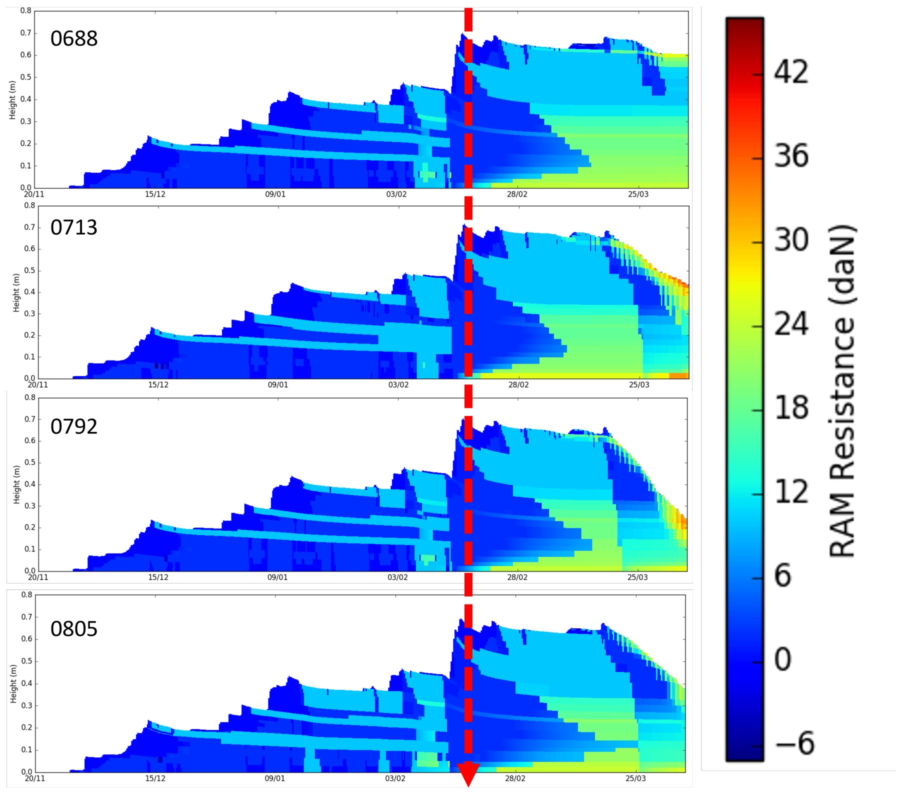

Figure 4.19: Simulated snow hardness. 0805 — forest scenario, 0792 — northeast in opening, 0713 — middle of opening, 0688 — southwest in opening.

hoar. The series of events is observed three times. There are more precipitation events than this, but the subsequent simulated grain metamorphosis has a different character.

The first snow that settles, acts in a different way compared to the processes described in the previous paragraph. Instead of the surface layer changing into melt forms, the whole snowpack goes from precipitation particles to more decomposed and rounded grains, and then to faceted crystals and depth hoar.

Towards the end of the accumulation season, there is a noticeable change in grain types for the whole snowpack. Larger parts of the snow turned into melt forms. For the snow fall in the beginning of February, all the snow that fell turn into melt forms after a few days. The snow that fell in mid-February became more decomposed before it changed into melt forms and depth hoar. Below this new snow layer, a layer which contained melt forms and faceted crystals were formed. Around March 6, this layer increased to 40 cm before turning into melt forms and faceted crystals. Within March 20 the snowpack consisted entirely of melt forms, depth hoar and faceted crystals.

Southwest and northeast have the most similar grain type evolution and distribution, while forest and open are different from southwest and northeast in different ways.

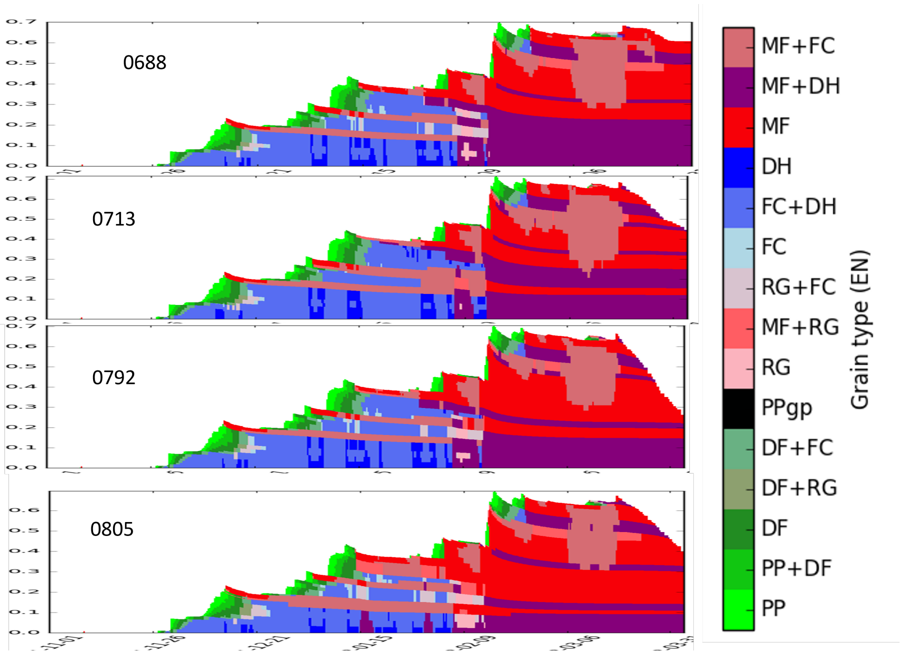

Figure 4.20: Simulated grain type. 0805 — forest scenario, 0792 — northeast in opening, 0713 — middle of opening, 0688 — southwest in opening

CHAPTER 5

Discussion

5.1 Comparing measurements

5.1.1 Data from open areas at Bjørnholt, Maridalen and Sørkedalen

The following subsection compares snow depth and temperature data from the Bjørnholt weather station with measurements of snow depth and temperature on the open sites in Maridalen and Sørkedalen, as well as snow depths from other weather stations in the area. The purpose is to point out differences between the sites and discuss the reliability of using weather data from Bjørnholt to simulate the snowpack in Maridalen and Sørkedalen. It will mainly be focused on snow depth, as this is the only variable measured in both places.

5.1.1.1 Snow depth

Figure 5.1 shows the measured snow depths from Bjørnholt and other weather stations in the relative vicinity of field measurement locations. It indicates how the field measurements of snow depth correlate with measurements from surrounding weather stations. It also shows how there can be significant differences within the same area. The snow depth in Sørkedalen seems to follow the same pattern as in Tryvannshøgda until mid— February. After February 15, snow depth in Sørkedalen is lower than in all other locations except Maridalsoset. Snow depth at Maridalsoset and Sørkedalen has a similar decrease in the period after February 15. To sum up, Figure 5.1 shows how snow depth in Maridalen and Sørkedalen differ from snow depth at Bjørnholt. It also indicates spatial variations in snow depth within a relatively small area.

Table 5.1: Elevations of the weather stations where snow depth data for comparing measurements were provided from.

Station	Elevation (m.a.s.l.)
Bjørnholt	360
Maridalsoset	173
Brunkollen	370
Tryvannshøgda	514

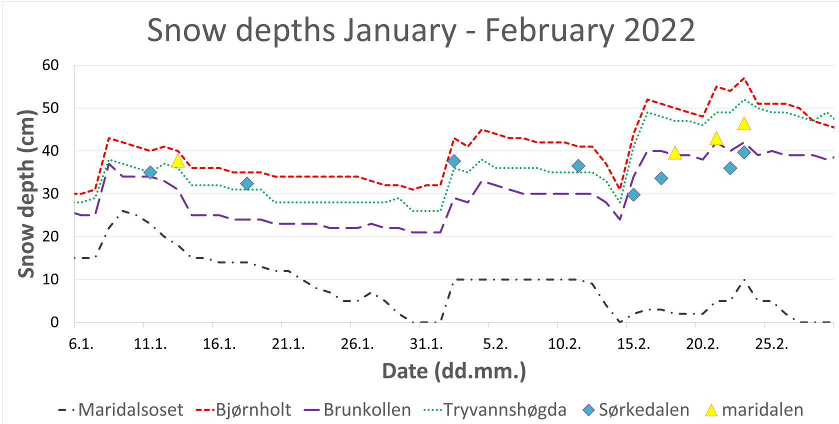

Figure 5.1: Measured snow depths from weather stations in the vicinity of field measurements. These are included to see the differences in measured snow depth between weather stations at different altitudes and positions. Elevations of the weather stations are shown in table 5.1. The data was provided from *Norsk Klimaservicesenter* n.d.

5.1.1.2 Temperature

Figure 5.2 shows the temperature measurements from field days in Sørkedalen and temperatures from the weather station at Bjørnholt. It shows that the measured temperatures are similar for some days to the measured values at Bjørnholt. However, there is a considerable uncertainty, as there are few data points to compare with the values from Bjørnholt. The field-measured temperatures are measured in an instant, while the data from Bjørnholt is the mean daily temperature.

5.1.2 Field measurements in open and forest

The aim of this subsection is to compare and explain the differences between field measurements in the open and forest. The idea is to highlight the observed differences in order to facilitate the next section, which will try to find to what degree the simulations are able to recreate the observed differences between snowpack in the open and forest.

5.1.2.1 Snow depth

There are observable differences between the sites and forest densities. Snow depths were highest in the open in Maridalen. In some cases, the difference varies depending on the time since snowfall, e.g., from early February in Sørkedalen. From February 2 to 11, there was a decrease in snow depth in the open site. In the same period, snow depth increased in the forest. A reason for this difference can be the unloading of intercepted snow from the trees, combined with increased compaction in the open area. A look at the snow pit profiles from the corresponding dates shows that the top layer in the open has changed character, from partly precipitation particles and partly decomposing and fragmented particles to entirely decomposing and fragmented particles. The

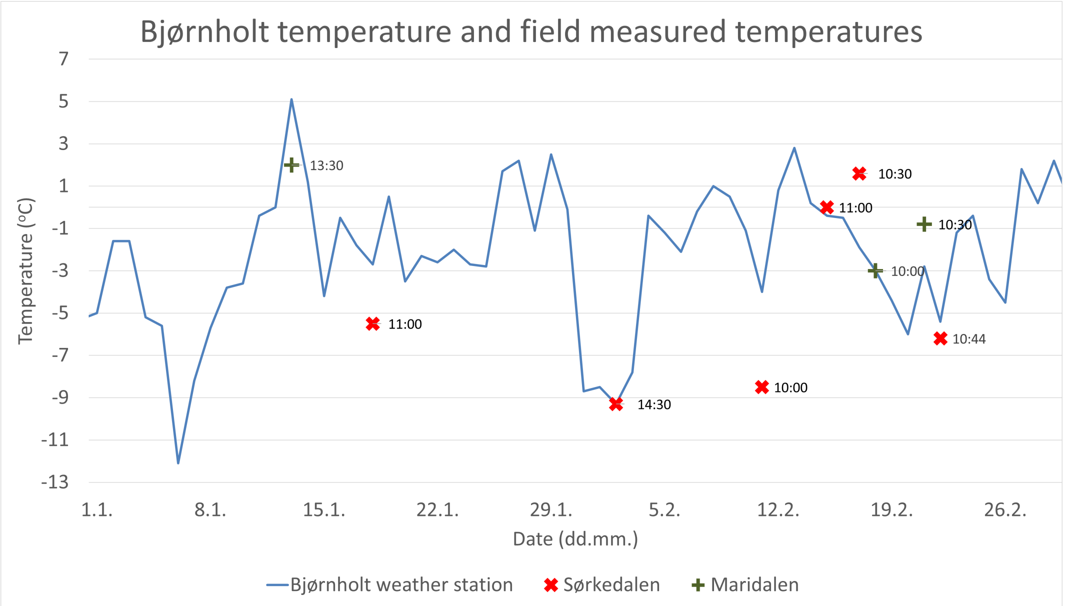

Figure 5.2: Temperature from Bjørnholt weather station and measured temperatures on field days from Sørkedalen and Maridalen. The timing of each field measured temperature is shown as a label.

change in grain type can imply sintering creation which will involve compaction. The exact change is seen close to the surface in the forest.

From February 17 to 22, there was a relatively equal snow depth increase in Maridalen open, Sørkedalen open, and Sørkedalen forest. Simultaneously, in the Maridalen forest, snow depth decreased. The difference in snow depth evolution between the two forest sites could be due to the different forest densities. The spruce forest in Maridalen not only has a higher number of stems per area, but the crown coverage is also higher in spruce compared to birch. In addition, the spruce forest can intercept more snow as it has a higher leaf area index and crown coverage. (Hedstrom and Pomeroy, 1998).

5.1.2.2 Temperature

Temperature differences between forest and open depending on the time of day measurements were made. There are mainly two ways that they can divide - how big and on which days are temperature differences observed. - compare gradients to other measured threshold values for near-surface facets

There are differences in temperatures between the open and forest on most field days (see Figure 4.4. After the snowpack went through a distinct change in character on February 12, it seemingly took longer time for the forest snowpack to come back to have a temperature gradient. This can be seen in the difference between temperature profiles from February 15 to 17. From February 11 to 15, the temperature gradient decreases from $-50\,^{\circ}\mathrm{C/m}$ to $-2\,^{\circ}\mathrm{C/m}$ in the open and from $-27\,^{\circ}\mathrm{C/m}$ to $0\,^{\circ}\mathrm{C/m}$. On February 17, there was a temperature decrease down to 12 cm below snow surface in the open pit, while the temperature was zero in the entire forest pit. It is important to note the timing of these measurements. With the exception of February 22, all field days started with measurements in the open and then in the forest. This will have an effect on the snow temperature as air temperatures generally increase from morning till mid day.

5.1.2.3 Snow stratigraphy

Grain types

Surface hoar Surface hoar observations closer to — and further away from — the forest implies that the forest affects surface hoar formation. Field measurements show differences in the appearance of surface hoar on two separate occasions; from January 11 to February 2, and on February 11.

On January 11 and 18, when measurements were conducted in the southwest part of the open field (location 2 in Figure3.1), surface hoar was observed under a 6.5 cm thick layer of fragmented decomposed particles. The surface hoar have possibly been formed around January 5 and 6. The mean temperature on Bjørnholt on January 5 and 6 was $-5.6°$ C and $-12°$ C, respectively. The snow depth data show no increase on these days, which is an indication of a clear sky, thus implying atmospheric conditions favorable for surface hoar growth. On February 2, when measurements were done close to the center of the open field, surface hoar was not observed in the snowpack. It is then a possibility that surface hoar were not formed in the middle of the field and that there was spatial variability within the same open field. However, considering that there were some days with temperatures above zero, the surface hoar could have metamorphosed into ice particles during this period. Thus, the data are insufficient to say something particular about the spatial variability of surface hoar growth in this period.

On February 11, there were visibly smaller surface hoar crystals in the middle of the field (1.5 mm long, see Figure 4.7), compared to the forest vicinity, the southwestern corner of the field (Figure 4.15). A reason could be the temperature increase on the snow surface due to increased solar radiation during daytime. This would decrease the air— surface temperature difference, which means less favorable conditions for surface hoar growth. The temperature at the surface could increase to the point where surface hoar crystals start to sublimate during the daytime, and it could destroy the formed layer. It is also a possibility that the forest did lower the wind speed so that it was possibilities for surface hoar growth in the forest vicinity but too high wind speed out in the field. To sum up, the measurements of surface hoar show a clear difference between surface hoar growth in different parts of an open field and their position compared to forests. However, it is impossible to say something specific about the reason for this difference due to insufficient data, e.g., on the energy balance.

Faceted crystals From the snow pit profiles in chapter4 it is observed that faceted crystals were found both in the forest in the open. There were two days where the grain form were observed exclusively in the open. Also, faceted crystals appeared more often as the only grain type of a layer in the open, whereas in the forest, it appeared more often as a secondary grain type.

A case which can be looked at is February 15–17. On February 15, no faceted crystals were observed in the snowpack in Sørkedalen. The snowpack consisted mainly of melt forms, and temperature was at 0° C. Two days later, faceted crystals were observed in both the open and the forested site. In the open, there was a distinguishable layer 5 cm below the snow surface, whereas in the forest, it appeared as a secondary grain type 5 − 14 cm below the snow surface. The measured temperature gradient in the upper 2 cm's of the snowpack was 50 K/m at 10:30 in the morning. If temperatures were colder earlier, it must have been steeper. The air temperatures had been above zero for a couple of days. This was followed by a temperature decrease and snow fall. Growth of near-surface facets have been observed under similar weather conditions (Akitaya, 1974). However, the observed temperature gradients were not that low (50 c/m), at least not in the morning. It could have been higher during the night, especially since the temperature stays at zero up to pretty close by the surface. The sequence of events are similar to what Birkeland, 1998 describes as melt-layer recrystallization.

Depth hoar The absence of depth hoar in snow pit profiles after February 11 could indicate that the temperature increase around February 12 had a stabilizing effect on the snowpack. As depth hoar typically form in the beginning of the winter when the snowpack is thin and temperature gradients are steep, it can remain as a weak layer even though temperature changes at the surface, due to the insulating properties of snow. In this scenario, it appears that the depth hoar has been metamorphosed in a similar manner in the forest and in the open. This could mean that the temperature has increased so much that the effect of forest is not visible on the measurements. Temperature profiles also indicate that there could have occured equilibrium growth and wet metamorphism.

Hardness and layering Due to limited data, it is difficult to point out a specific trend in the evolution of hardness and layering in the snow cover. However, some differences stick out and can be discussed. One thing is how the hardness varies differently in the forest. In the open field, there was a more gradual decrease. It starts at 120 N on January 11, and although there are some fluctuations, the hardness gradually increases and ends at 460 N on February 22. The hardness in the forest fluctuates more. An example is on February 18—21, where hardness increased from 278 N to 741 N in the forest. In the open, the hardness went from 376 to 461 on the exact dates.

Another factor that is different between the forest and the open is the number of layers. Except for one day when there was an equal amount, more layers were in the open. This can be a result of spatial variability but also the layering changes between days. Although measurements are too scarce to indicate a difference, they might show a similar trend to other studies. Teich et al., n.d. found, for instance, that snow stratigraphy varies more in dense forests compared to in open fields.

Measurements of shear strength might confirm the uneven distribution of a weak layer that Gubler and Rychetnik (1991) suggests. Higher shear strengths with lower deviations in the open vs lower shear strengths with higher deviations in the forest indicate a weakening effect on the weak layer. On the other hand, an important factor for an avalanche to release is a persistent weak layer which is even as well. These measurements suggest that forests can lead to a weakening of the weak layer, but also that the forest can decrease the lateral consistency of the layer.

5.2 Comparing simulations and measurements

This section aims to discuss how CROCUS is able to simulate the highlighted differences from previous sections. Both the capability of CROCUS to simulate the snowpack in the open and the differences between the open and the forest will be assessed.

5.2.1 Simulating the snowpack in the open

The intention of the following part is to compare the snow pit profiles from certain days to the simulated snowpack. This is done to assess the functionality of CROCUS to simulate snowpack in the open, given the current assumptions and conditions, before evaluating to what the degree the model is able to reproduce differences between snow in the forest and in the open.

5.2.1.1 Snow depth

Figure 5.3 shows how the snow depth that was simulated in Sørkedalen differs from the measured snow depth values at Bjørnholt weather station. Remember Figure 5.1 which shows that the measured snow depths in Sørkedalen are even lower than at Bjørnholt. The main issue is that snow depth does not decrease at the same in the simulations as in the measurements. For example, in mid–January, the measured snow depth decreases almost 10 cm in a few days, while simulations show barely any decrease at all. The difference is observed throughout the winter, and becomes a consequential error that culminate in a 30 cm difference in snow depth at the beginning of April. The snow depth increase seems to be more correctly simulated.

5.2.1.2 Snow stratigraphy

Grain types It is difficult to give a complete comparison of the snowpack stratigraphy due to the scarcity of snow profiles. On some days however, snow pit profiles show similar grain types as in the simulations, and the following section will discuss some of these correlations.

One correlation is the depth hoar (DH) layer at the bottom of the snowpack. The layer can be observed in all snow pit profiles from January 11 — February 11, and in the simulations for the same period. However, the snow pit profiles shows that the DH–layer varied in thickness in this period. Around February 9, simulations show that the lowest layer changes from faceted crystals(FC) and DH to melt forms(MF) and DH (Figure 4.20). The snow pit profiles from February 2 and 11 (Figure 4.5 and 4.7, respectively) also shows this grain type change in the bottom layer. Although it is not possible to determine the exact time this happens, the data could indicate that it was between February 2 and

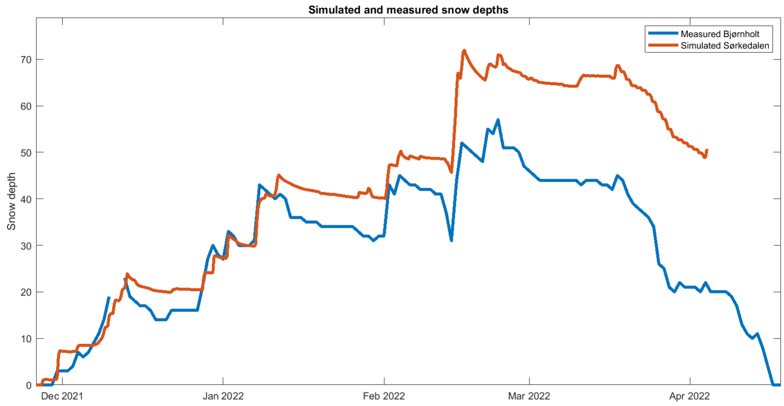

Figure 5.3: Measured snow depth at Bjørnholt and simulated in Sørkedalen.

11, which seems to fit with the simulations. The change in snowpack character around February 12 can be observed in the bottom layer of the February 15 profile. On this day, the snowpack consisted entirely of rounded polycrystals (a type of melt form), with some exceptions of thin ice layers. It was almost the same for the simulated snowpack, the only difference being that it contained some depth hoar as well.

Another important feature that is worth mentioning, is the occurrence of faceted crystals. The case mentioned in section 5.1.2.3, where faceted crystals might have been formed in only two days from February 15–17, can also be seen in the simulations. In Figure4.20, in the open scenario, there is a layer of FC and DH 10 cm below the snow surface. This is at the same height as in Figure4.11. This is an indication of the ability that CROCUS have at simulating weak layers in a snowpack.

Hardness layThere are observable similarities between the simulated and measured hardness in the open, e.g., the two harder layers around 20 and 30 cm above ground. They can be seen from the beginning of January to the beginning of February in Figure 4.19. Similar hardness pattern is observed in the snow profiles from February 2 and 11 (Figure 4.5 and 4.7). However, the simulated hardness values of the two layers were lower than what was shown in the field measurements. The simulated RAM resistance of the middle layers was around 120 N, while the measured layers ranged from medium to very hard, which corresponds to a RAM resistance of 175–1200 N (see table 3.1 for the relation between different hardness units).

After February 11, the observed hardness change is to some degree similar between simulations and measurements. First, hardness decreased rapidly around February 12, which can be seen in both the simulations and the measurements. Then, the measured hardness increased quite similarly in the whole snowpack, wheareas the simulated hardness increased more at the top and bottom. On February 22, the measured hardness was softest at the top, and then harder towards the bottom, which was similar to the simulations.

However, the simulated snowpack did not completely have an even increase from surface to bottom before mid-March. A possible explanation to this is that because the snow depth was higher in the simulated scenario, the time it took for the snowpack to stabilize was longer than in the observations where the snowpack was thinner.

5.2.1.3 Temperature

Temperature gradients It is possible to get an impression of how well CROCUS is able to simulate the temperature in the snowpack by comparing the simulated temperature profiles with the ones that were measured. There are noteworthy similarities between the simulated and observed temperature profiles on six days out of ten snow temperatures measurements in total. The weather change event on February 12 which altered many of the snow parameters, also had a persisting effect on the temperature profiles, and can be seen for several days after the event. There is, however, a high level of uncertainty related to assessing the accuracy of the simulations by evaluating temperature profiles measured at one moment.

5.2.2 Ability of CROCUS to simulate differences between forest and open

For this part, the focus is to compare the measured differences between snowpack in the forest and in the open, to the simulated differences. Hence, seeing if the differences that were considered in section 5.1.2 can be seen in the simulations as well.

5.2.2.1 Snow depth

Differences between simulated scenarios It is possible to separate the four different forest scenarios based on the simulated snow depth, however the differences are not very big until the main snow melt starts in mid–March. The first observable difference in snow depth change is observed around January 14. There is some decrease in all scenarios, but snow depth in the mid-forest scenario drops after some time, whereas the open scenario has a steadier decrease. Because forests increase the longwave radiation to the snow surface, it seems reasonable that there is more melt in sub-canopy snow than in open areas. Especially in Norway in winter, when the sun does not contribute as much to the energy budget as other energy sources such as longwave radiation from the atmosphere.

The differences in simulated snow depths between forest scenarios in the snow accumulation period, show that the values are highest in the open and lowest in the forest. However, there are small differences, which make them not able to count as significant differences. In the ablation period, starting around mid-March, the differences are larger, and seems to fit with findings from other studies (Golding and Swanson, 1986). However, due to the lack of field measurements in the ablation period, it is not possible to confirm whether or not these simulations reflect how the snow cover actually evolved.

How do differences between simulated scenarios compare to the observed differences? The simulated snow depth decrease is generally too low compared to the field measurements. This snow depth discrepancy is also observed when comparing simulations to the data from the weather station at Bjørnholt. Considering that only the energy balance was modified, and not how much snow was held back from reaching the ground due to interception, one could maybe assume that at least the snow melt was simulated in a correct way. However, as this was not the case, it could be that the energy balance alteration was to conservative. It is also an important aspect that the images that were used to calculate the sky view fraction were from a different place with a different tree type, which also could have an effect. Hence it is an important aspect to consider if similar studies are to be conducted later.

5.2.2.2 Snow stratigraphy

Differences between simulated scenarios The overall differences in snow stratigraphy between the simulated scenarios are quite minimal. The differences are thus at a more detailed level, and to a large extent concerning small, insignificant variations. Insignificant in that sense that if, e.g., a layer contains faceted crystals and depth hoar instead of only depth hoar, the variation will not be of great importance when assessing avalanche hazard. These small differences, however, are important when the effect of forest on avalanche hazard is to be assessed, but it is not possible to verify the differences based on the simulations conducted in this study.

Similarities between simulated and observed snowpack differences between the forest and the open Differences in snow stratigraphy in the forest and in the open are more convincing in the observations compared to simulations. The simulated differences are small, whereas the observed differences are noticeable when it comes to several factors i.e., timing and spreading of changes in the snowpack resulting from weather change.

Hardness The snowpack hardness evolution after February 12 is perhaps where the field measurements show the most outstanding hardness differences between the forest and the open is observed. The simulations show a slower change compared to both forest and open. After February 12, the simulated hardnesses looks more like forested than open. Most likely, the layers that were observed in the simulations are not the ice layers, but just layers with slightly higher hardness. The hardness is too low to be ice (Fierz et al., 2009).

5.2.2.3 Temperature

5.3 Predicting forest effect on avalanche hazard using simulations and field measurements

There were differences between the simulated snow packs in the different forest scenarios, but these were seldom similar to the observed differences. If there were visible similarites, they were insufficient to say if the difference was significant. CROCUS has proved to be able to reproduce snow cover earlier (Brun et al., 1989), however data for the simulations were then taken at a site closer to the observations. Problems arised with subsequential errors, regarding e.g. snow depth. This was problematic as the simulations shows underestimated snow melt, which resulted in a much higher snow depth in the simulations after some time.

The applied method of comparing snowpack simulations to snowpack observations works relatively well concerning snowpack in the open, considering the applied assumptions. Much of the same features regarding all parameters such as temperature, snow stratigraphy, and snow depth have been observed in both observations and simulations. There is, however, another case regarding how simulations are able to reproduce the differences between the open and forest. Although, there are indeed differences between the simulated forest snowpack and open snowpack, which could indicate that parts of the framework used in this study can be used in further studies on the subject.

5.4 Limitations and further work

Look more at the simulated temperature differences in periods where metamorphism where observed in the snowpack. This could give information whether CROCUS is able to simulate temperature differences between the surface and air that could facilitate for possible weak layers in the snowpack.

A possible improvement of the approach in this thesis would be to direct the focus more towards differences not only in forests and openings, but also look at different openings and the pack at different points in the same opening. Some observations of this were done in the field, but they were quite limited. An increased focus on this could provide an increased amount of factor to consider regarding the influence of forests on the snowpack.

Another possible adjustment, is to move the field measurements location closer to the weather station. This would, however, change the focus of the thesis more towards evaluating the performance of CROCUS more directly, and not how it works at simulating snowpack in other locations. It could as well be of interest to

To include interception in the simulations, could be a good first step towards more realistic simulations. This would increase the simulated snow depth, which could potentially show snowpack processes in the simulations that were more similar to the observed ones.

CHAPTER 6

Conclusion

In this study, field investigations of the snowpack in and outside the forest have been conducted to study the effect of forest on the snowpack. In addition, simulations of the snowpack under different forest cover scenarios were carried out using weather data from a weather station located six km from the field measurement location. This difference in location and elevation was taken into account. The different forest simulation scenarios were created by modifying the radiation balance of the snow cover. Further, the observed and simulated differences in and outside the forest were compared to evaluate the modeling approach.

Both the simulations and the field measurements showed differences between the forest and the open, and the magnitude and character of these differences did occasionally correspond. Snow started settling on the ground at a similar time, and snow also disappeared at almost the same time in the simulations and measurements. There were also similar temperature profiles on several field days. There was also correspondence between the timing of the appearance of different layers, such as depth hoar, which appeared at similar times. However, an important note is that the field observations were often too scarce to prove or disprove the simulated differences. The simulations could have been improved by using data from an area closer to the field sites, and it could have been possible to simulate the snowpack more realistically.

Hopefully, the methods and reflections around the effectivity of the model and field measurements done in this thesis could provide valuable information on further investigations of forest effect on avalanche release probability.

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