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Spatial and temporal variability of taiga snow properties during melting period in Sodankylä, Finland

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Abstract. This study investigates the temporal and spatial variability of physical snow properties during the melting period in taiga snowpack conditions in Sodankylä, northern Finland. Weekly snow pit measurements — including stratigraphy, temperature, and density — were conducted at four locations over an eight-week period from March to May in 2023 to assess landscape-scale variability. At three sites, the average spatial variability of automatically measured snow height over time was 7.4 cm (9.7%). Density measurements using the snow water equivalent tube showed higher spatial variability compared to those made with a density cutter, and this variability increased during melt. Differences between measurement techniques exceeded differences between locations. Peaks in density profiles were mainly linked to melt-freeze crusts and ice layers. Depth hoar was consistently found in lower snowpack layers before melting, reaching a maximum relative height of 21.5%. The appearance of melt-freeze crusts following short-term temperature shifts highlights the snowpack's sensitivity to daily thermal cycles. Initial wetness was observed mid-snowpack, suggesting that refreezing from cold nights operates top-down, not affecting the full depth. Moist and wet layers became more prevalent in the upper snowpack, while the wettest layers accumulated at the base rather than being evenly distributed.

1. Introduction

Snowpack plays a key role in the regional water cycle and energy balance. Snow properties such as height, density, temperature, and stratigraphy are crucial for understanding snowpack evolution, melt dynamics, and water availability (e.g. Colbeck, 1991; Sturm et al., 2010). They influence surface energy balance, runoff generation, and the accuracy of remote sensing and climate models (e.g. Marks and Dozier, 1992; Pomeroy et al, 1998; Foster et al, 1987; Derksen and Brown, 2012). Monitoring these properties is essential for hydrological forecasting and assessing climate impacts in snow-covered regions. The rise in air temperature is predicted to shorten the snow period, as well as to increase the wetness of the snow

(Luomaranta et al., 2019). The increase in climate variability is expected to bring heavier precipitation events, which will lead to changes in the average snow height, the snow water equivalent (SWE), and the internal snow structure, e.g., density and insulation capacity (Luomaranta et al., 2019).

Snow on the ground is so close to its melting point that its properties are constantly changing. The changes referred to as metamorphism are caused by internal processes, such as water vapor pressure and temperature gradient within the snowpack (Fierz et al., 2009). Different metamorphic processes in natural snow happen at the same time resulting in a layered snowpack that is highly variable in both spatial and temporal dimensions (Sturm and Benson, 2004).

When making a classical snow profile, layers and grains are classified following the International Classification for Seasonal Snow on the Ground by Fierz et al. (2009). Boundaries between each layer can be identified looking at grain size, shape, wetness and arrangement of bonds, which are impacting the hardness and density of the layer. Under natural conditions layers have irregular boundaries and can be hard to identify, leading to a big error range and subjective bias when detecting them.

There is a huge amount of spatial variability in the layer stratigraphy, as it is influenced by external factors, climatic conditions and internal processes (Sturm and Benson, 2004). Besides the internal processes, external factors such as wind, vegetation or topography have a huge influence on layer heterogeneity (Sturm and Benson, 2004). Shrubs and trees can enhance temperature gradients and large upward water fluxes, resulting in more and heavier depth hoar formation (Royer et al., 2021).

The melting period is critical, as snow properties change rapidly, influencing runoff generation, ground thaw, and surface energy balance. These changes have significant implications for hydrology, climate research, and ecosystem processes (Pomeroy et al, 1998; Marks and Dozier, 1992). Improving our understanding of the temporal and spatial variability of snow properties during this period is essential for refining hydrological models, enhancing climate predictions, and increasing the accuracy of remote sensing applications in snow-covered regions.

Taiga snowpack is characteristic of boreal forest regions and typically it consists of a cold, dry snow cover with complex stratigraphy shaped by low temperatures, intermittent snowfall, and forest canopy effects (Sturm et al., 1995; Sturm and Liston, 2021). It often includes layers of depth hoar, faceted crystals, and ice crusts, with significant seasonal changes during the spring melt period. While there have been some studies about spatial and temporal variability of taiga snowpack characteristics in Sodankylä for winter conditions (Hannula et al., 2016), no similar study exists for the spring melting season. Variability of melting snow properties in Colorado, US has been shortly discussed by Lund et al. (2022). Currently,

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there is uncertainty in how well spatial variability is captured across heterogeneous landscapes in the melting season. There exists also a limited amount of data on spatial variability from different field sites during the melting period.

The study is conducted in the Arctic Space Centre of Finnish Meteorological Institute located in Sodankylä, northern Finland, which is an extensive field site for validation and calibration of satellite observations as well as for developing measurement technologies and retrieval algorithms. The Arctic Space Centre has long-term meteorological records and snow pit observations have been made regularly since 2006 (Leppänen et al., 2016). The research station area has various microenvironments including open areas, forests and bogs. Information on spatial and temporal variability of snow properties in melting period is therefore crucial for various applications.

2. Methods

During a period between the 20th of March 2023 and the 10th of May 2023 weekly snow measurements were carried out at four different locations around the Arctic Space Centre in Sodankylä, northern Finland. The four selected sites, visible in Fig. 1, were chosen due to their different environmental surroundings, representing vegetation and soil variability. Table 1 presents precise details regarding each measurement's timing and location. The four sites are: Lichen Fence (N67.367100 E26.634740), Forest near the Airport - shortly called Airport (N67.384250, E26.625290), Intensive Observation Area (IOA) (N67.36179, E26.63378) and Sounding Station (N67.366890 E26.629890).

The measuring site Lichen Fence was located within the boreal forest (Fig. 1b). It was surrounded by trees, which kept the location shaded throughout the whole day and shielded from bigger animals with a fence, so that the snow cover remained undisturbed by footprints from foxes or rabbits. The biggest influence of the fence was keeping away the reindeer, so that a thick layer of moss and lichen formed. This contrasts with the forest near the Airport. This measuring point was not shielded, so the layer of moss and lichen below the snowpack was thinner. Located on the edge of a forest the Airport was more sparsely surrounded by trees (Fig. 1c). Therefore, it was only shaded by trees in the morning and was in full sun in the afternoon.

The measurement point at the Intensive Observation Area (IOA) was located in a shielded area in a forest opening (Fig. 1d). However, the fence did not seem insurmountable, so that small animals such as wood grouse were sighted, which could have influenced the snow. A few irregular trees cast shadows, but the influence of these is significantly less than at the Lichen Fence or at the Airport, so the measuring site was predominantly in the sun. The Sounding Station is the fourth measuring site. It was located in the middle of the Arctic Space Centre and therefore close to buildings and a tarmac road, which is very rarely used (Fig. 1e). However, once the snow on the road has melted, the tarmac surface naturally has a warming effect on the surrounding area due to the low albedo. The measuring site was also completely exposed to the sun throughout the day.

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The snow pit measurements were carried out following the International Classification of Snow on the Ground (Fierz et al., 2009), using methods presented by Leppänen et al. (2016) and equipment visible in Fig. 2. A traditional snow profile was determined, including snow height, temperature and density profiles sampled every 5 cm, as well as the bulk density of the whole snowpack, and the layer stratigraphy: layer height, hardness and wetness, grain type and size.

In addition to the manual measurements, the Arctic Space Centre has automated snow height measurements made with SR50 (Campbell Scientific) sensors at Sounding Station and IOA. At IOA, there are two sensors, one located in the forested area and another one in the open area. There are no automated snow height measurements at Lichen Fence and Airport sites.

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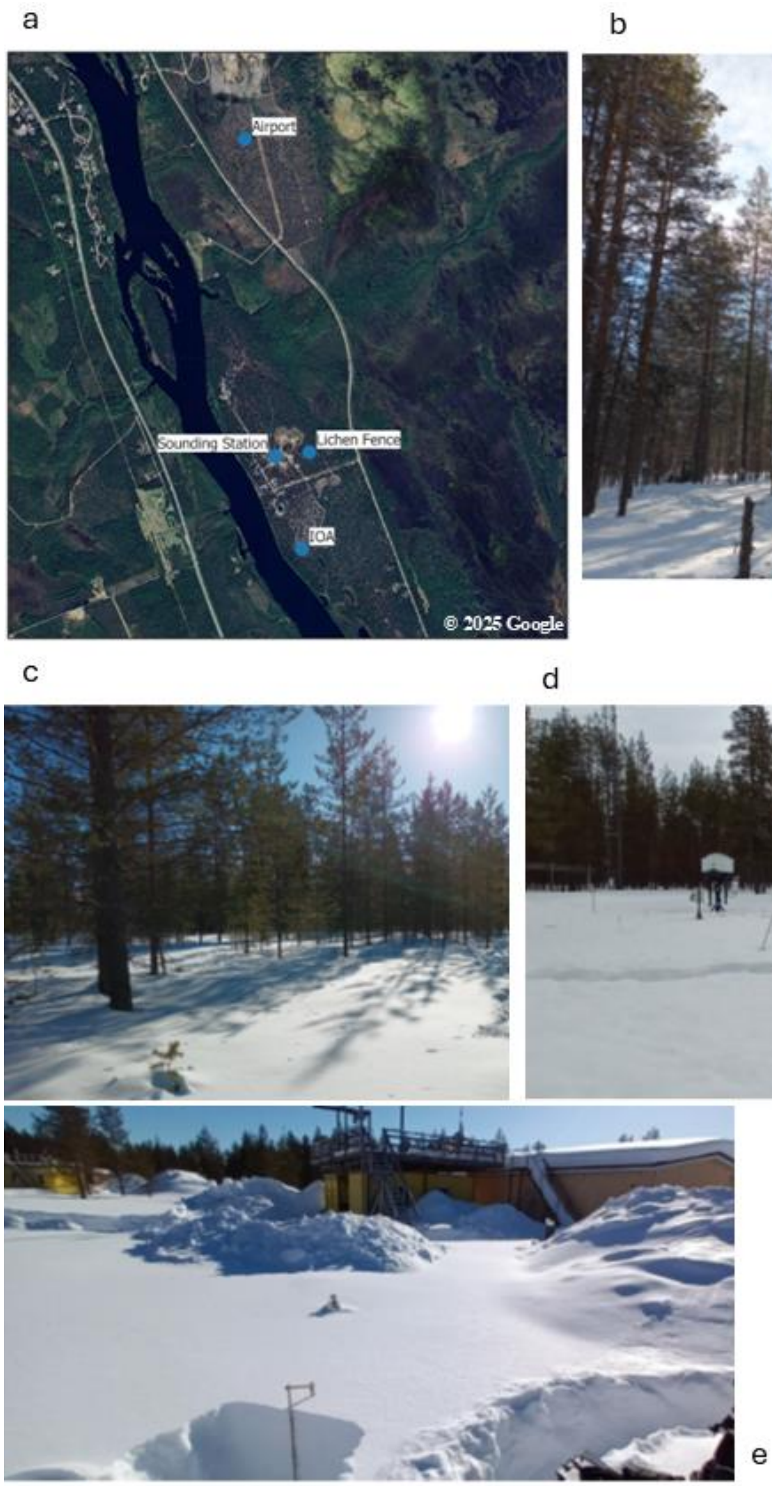

Figure 1: a) Locations of the field measurement sites and photos from b) Lichen Fence, c) Airport, d) IOA, and e) Sounding Station. Map data © 2025 Google.

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Table 1: The timetable of conducted measurements is sorted chronologically.

Date	Time	Site
21.03.2023	11:40	Sounding Station
21.03.2023	15:00	Lichen Fence
22.03.2023	10:22	IOA
22.03.2023	13:45	Airport
27.03.2023	12:20	IOA
27.03.2023	14:30	Sounding Station
28.03.2023	10:00	Airport
28.03.2023	13:20	Lichen Fence
05.04.2023	11:10	Sounding Station
06.04.2023	08:10	IOA
06.04.2023	10:20	Airport
06.04.2023	12:00	Lichen Fence
13.04.2023	08:05	Airport
13.04.2023	10:30	Sounding Station
12.04.2023	10:30	Lichen Fence
13.04.2023	12:30	IOA
19.04.2023	13:10	IOA
19.04.2023	15:10	Sounding Station
20.04.2023	12:00	Airport
20.04.2023	14:15	Lichen Fence
25.04.2023	10:15	Sounding Station
25.04.2023	11:15	Lichen Fence
25.04.2023	15:42	Airport
26.04.2023	09:05	IOA
04.05.2023	08:20	IOA
04.05.2023	10:00	Airport
04.05.2023	12:10	Lichen Fence
04.05.2023	13:00	Sounding Station
10.05.2023	10:11	IOA
10.05.2023	10:50	Sounding Station
10.05.2023	11:20	Lichen Fence
10.05.2023	13:20	Airport

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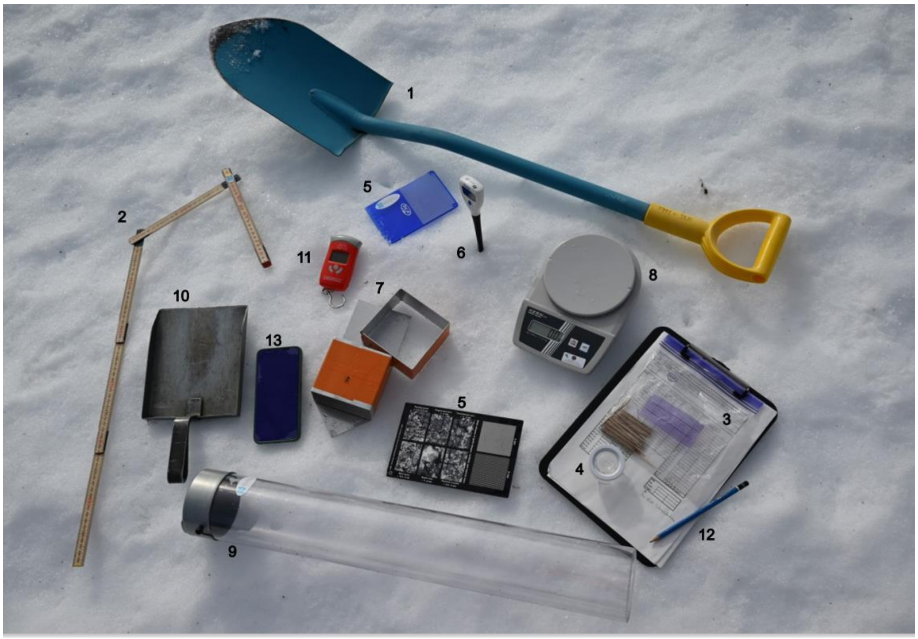

Figure 2: Measurement equipment: 1. Shovel for digging the snow pit, 2. Folding ruler for measuring snow height, 3. Toothpicks for marking layer interfaces, 4. Magnifying lens for classifying grain size and type, 5. Crystal card with 1 mm and 2 mm reference grid for classifying grain size and type, 6. Digital thermometer to measure air and snow temperature, 7. Density cutter to measure weight of a fixed volume and estimate the density, 8. Digital scale to measure the weight of the snow within the density cutter, 9. Snow water equivalent tube to take a snow sample through the whole snowpack for bulk density, 10. Flat shovel used whenever snow was higher than the length of the tube, 11. Digital scale to measure weight of snow in a plastic bag sampled with the tube, 12. Paper and pen for note taking, 13. Mobile phone to take documenting pictures. Photo credit: Lisa König.

3. Results

3.1. Snow height

The spatial variability of the automated continuous snow height measurements is shown in Fig. 3a. The maximum standard deviation is reached on 12th March with a value of 9.9 cm, and a mean snow height of 68.6 cm. This corresponds to a percentage of 14%. The average spatial variability over time equals 7.4 cm or 9.7%. The maximum mean snow height is reached on 30th March. The greatest snow height can be found at the Sounding Station. At the IOA forest station the lowest snow height, as well as the earliest beginning of the snow-free period can be found. Accordingly, the IOA forest area is snow-free starting from 11th May, while the IOA open area is snow-free from 16th May and the Sounding Station from 23rd May.

In the manual snow pit observations, the Sounding Station is the earliest to be snow free. The smallest maximum amount of snow was found at the Airport. While the snow heights manually measured at the IOA open area precisely match the automatically measured values, the results recorded at the Sounding Station show a downward deviation towards the

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automatically measured snow height (Fig. 3b). Until 25th April, the snow height at the Airport is consistently lower than at the other locations. From 25th April onwards, the snow height at the Sounding Station becomes the lowest, with the Sounding Station also being the first station to become snow-free. Qualitatively, the spatial variability of the manually measured snow heights seems to be even lower than the spatial variability of the automatically determined snow heights.

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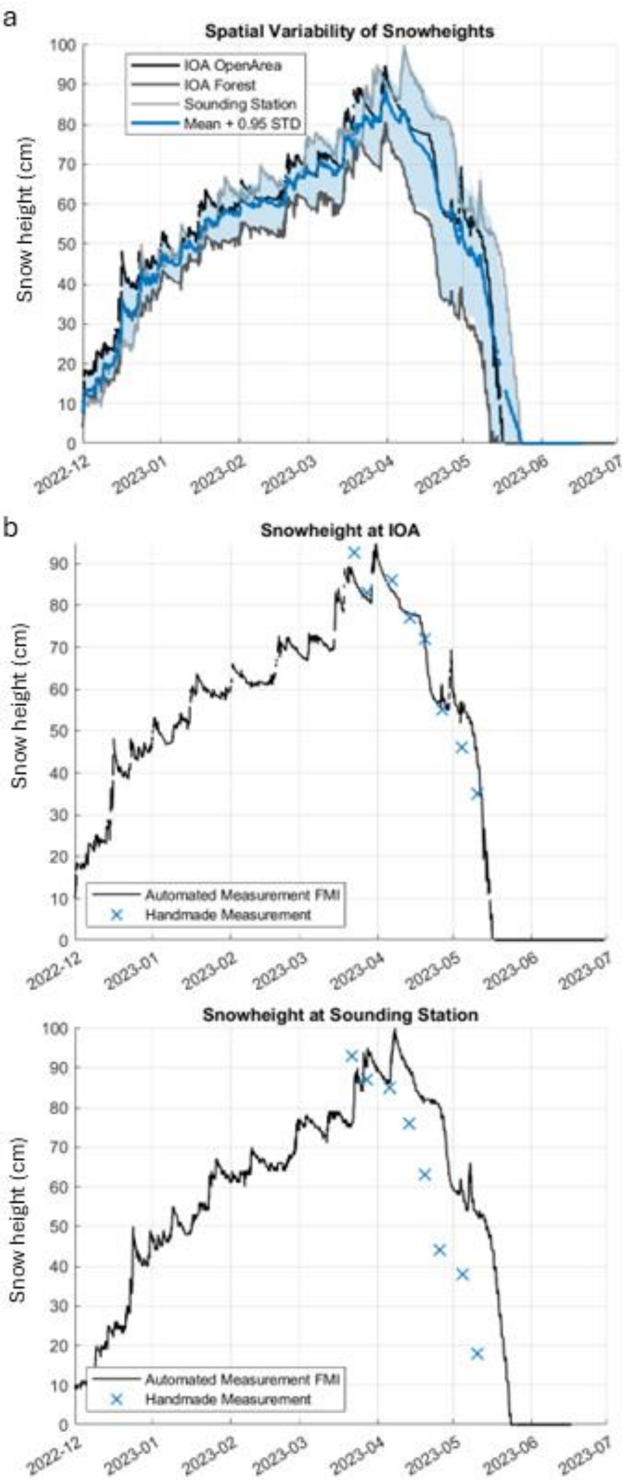

Figure 3: a) Automatically detected snow height. b) Comparison of automatic (black lines) and manual (light blue crosses) snow height measurement.

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3.2. Density

The spatial variability of density measurements made with the SWE tube is greater than for the density cutter, and it increases during the melting process. The difference between the four measurement locations is smaller than the difference between the measurement techniques. The standard deviation for the tube ranges from 10.36 kg/m^3 to 17.15 kg/m^3 and for the density cutter 4.85 kg/m^3 to 14.97 kg/m^3, except for last week, where outliers occurred due to the very low snow height and the very wet or soaked snow. The spatial variability is smaller than the systematic measurement error, visualized in Fig. 4, and significantly smaller than the difference between the two measurement methods. The densities measured with the density cutters show consistent curves across all four locations, whereas the tube measurement displays more noticeable deviations, as well as a strong outlier in the last week.

In March and early April all locations show an initial gradient with increasing density from the upper layers near the surface to deeper layers, with a small decrease in density for depth hoar layers. As soon as the melting process starts, around 20th April, there is a noticeable increase in density. This increase continues until late April and early May, where densities often peak at values close to 500 kg/m^3. With increasing wetness, the snow density nearly doubles, which was also observed in the bulk density evolution. Several peeks in density profiles can be identified at various times and locations. These are mostly caused by melt-freeze crusts and ice layers, which can be seen when comparing the density with the layer stratigraphy in Fig 6.

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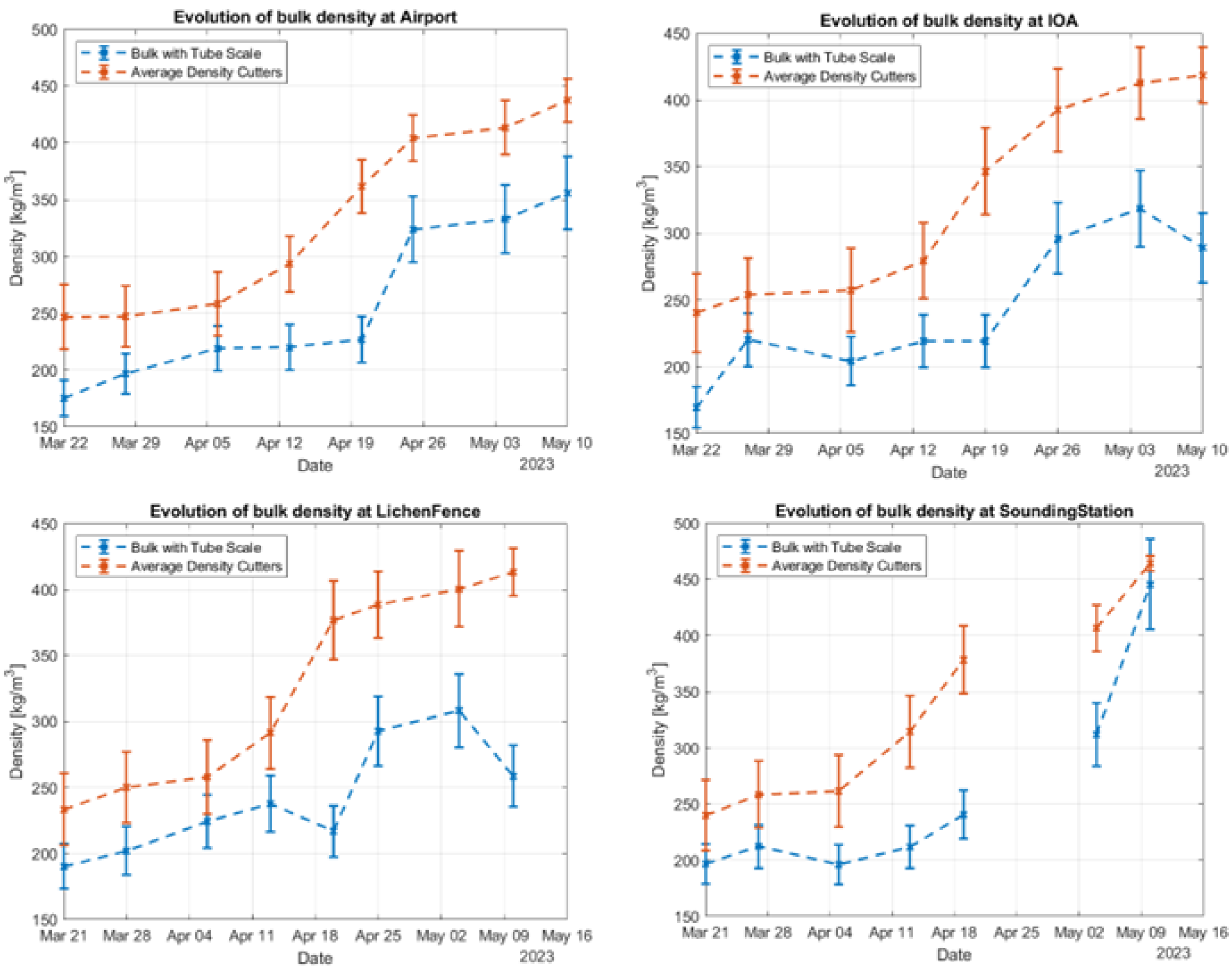

Figure 4: Evolution of the bulk density for all locations. The indicated error bars correspond to the measurement uncertainty estimations by Kaasik et al. (2023).

3.3. Layer Stratigraphy

When examining the entire layer stratigraphy, certain differences and symmetries between the locations can be observed (Fig. 5). In general, the early April snowpack across all locations begins with various snow types including precipitation particles, decomposing and fragmented precipitation particles, faceted crystals and depth hoar. A thin ice layer, presumably formed by melting and refreezing, can be identified at a snow height of approximately 50 cm throughout the entire period. This layer is observable at all locations, sometimes more pronounced, sometimes weaker.

Depth hoar is prominently found in the lower layers across all sites, peaking around mid-April, and its maximum amount recorded on 13th and 14th May. The average peak height of the depth hoar reaches 15.75 cm ± 4.03 cm, which corresponds to a ratio of depth hoar to total snow height of 21.57 % ± 3.98%. Comparing the measurement locations, the IOA shows the

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highest maximal amount of depth hoar, 20 cm, which corresponds to approximately 26% of the total snow height. At the Sounding Station and Lichen Fence similar starting heights of around 12 cm are observable with a slight difference in their peak values, reaching about 18 cm and 16 cm, respectively. The amount of depth hoar at the Airport starts lower at around 10 cm and peaks at approximately 16 cm. After the peak around 13th April, all locations exhibit a rapid decline to zero by 25th April. Moving towards late April and May, there is a transition from depth hoar to melt forms combined with a general reduction in snow height across all sites. The layers shift predominantly melt forms and melt-freeze crust indicating increased melting and refreezing highlights the dynamic transformation within the snowpack as the season progresses.

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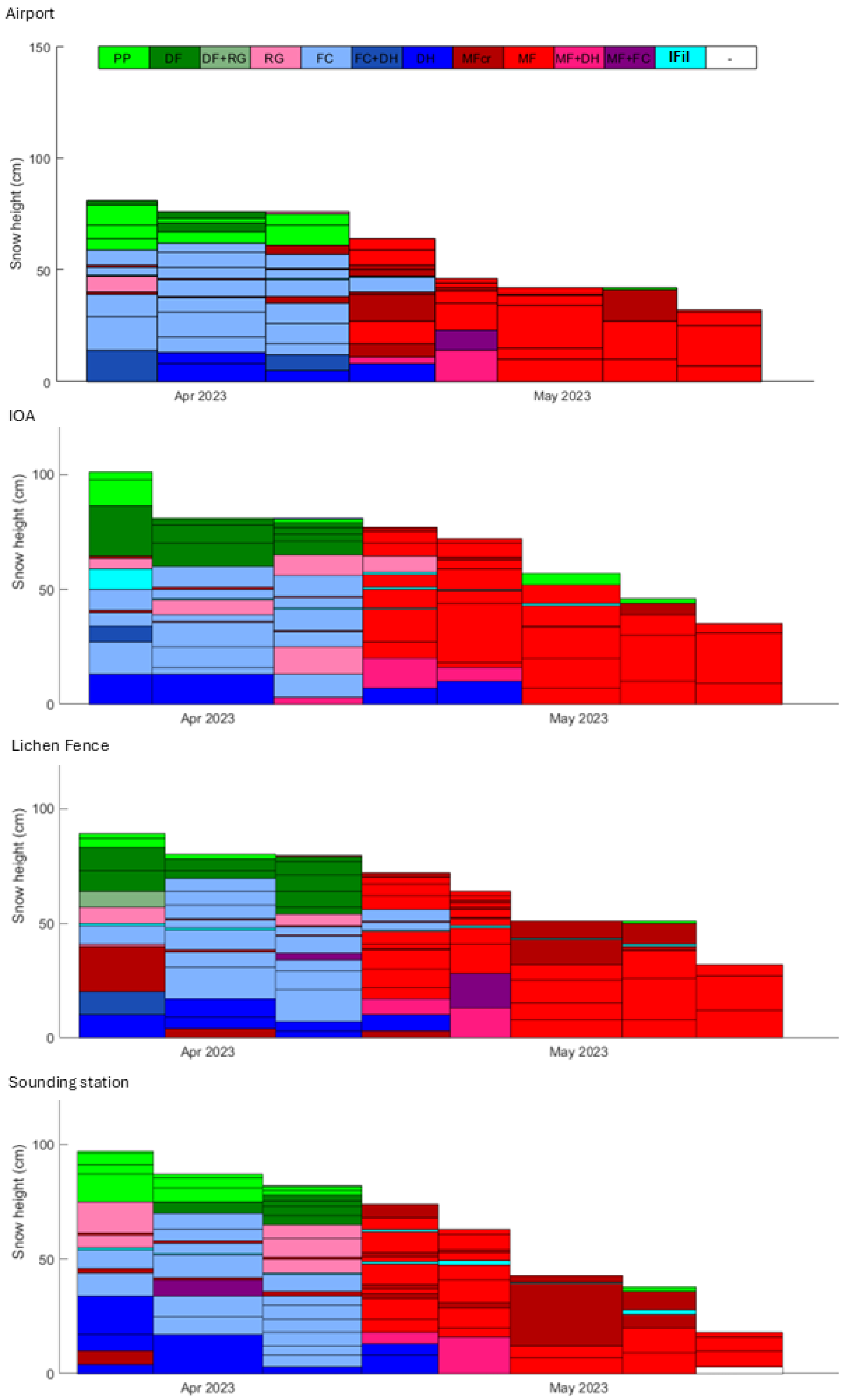

Figure 5: Evolution of layer stratigraphy.

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3.4. Temperature and wetness

Across all locations, the temperature profiles follow a consistent pattern over time. In March, the snowpack begins with very cold temperatures at the surface, which increase gradually towards the ground. By early April, the surface temperatures begin to rise until by mid-April, the temperature profiles become less steep and closer to T = 0 °C in the lowest layers. By late April and early May, all locations show an isothermal snowpack with T = 0 °C throughout the whole snowpack.

The evolution of wetness shows a highly heterogeneous pattern (Fig. 6). Until 13th April, no wetness was detected, but from that point onward, wetness within the snow pit increased. Spatial variability is evident across both spatial scales - between different locations as well as within a single snow pit. The first moist snow was detected on 12th April at 10:30 AM at the Lichen Fence. It was located in the middle of the snowpack and spanned about one-third of the total snowpack height. A similar pattern was observed on 13th April at the Airport around 8:30 AM. At 10:30 AM on 13th April, wetness was detected at the Sounding Station, showing a moist section at the bottom of the snowpack. Later that day, the snow at the Airport was entirely dry except for the second uppermost layer, where a few centimeters were moist. The near-surface melting process began at all locations from 19th April onwards. The total amount of moist and wet snow layers increased, primarily in the upper layers. This melting of the upper layers occurred during the day due to solar radiation causing the Lichen Fence snow pit, measured later in the day, to be the wettest.

On 25th/26th April the snow profiles at IOA, Lichen Fence, and the Sounding Station are dry and refrozen, whereas the snow at the Airport remained as wet as it was on 2nd April. IOA, Lichen Fence, and the Sounding Station were measured before noon, while the Airport's measurements were taken around 4 PM, after a full day of shortwave radiation exposure. This observation aligns with the stratigraphy findings, as a thick melt-freeze crust was measured in the snow pit on that day (Fig. 6). At Lichen Fence, IOA, and the Sounding Station, the upper layers of snow were dry, with increasing moisture observed deeper down.

If the snow had already started melting by 25th/26th April, this trend intensified through 4th May and even more by 10th May. The snow height continued to decrease, and the snow became very wet. However, the trend persisted that the wettest snow layers were at the bottom, rather than being homogeneously distributed throughout the snowpack. The trend that the amount of wet snow also correlated with the time of measurement - i.e., later in the day, the wetter the snow - was not observed. Instead, from 4th May onwards, the IOA appeared to be the wettest snow pit, even when measured in the morning. By 10th May no continuous snow cover remained, and the snow wetness reached "soaked" for most locations.

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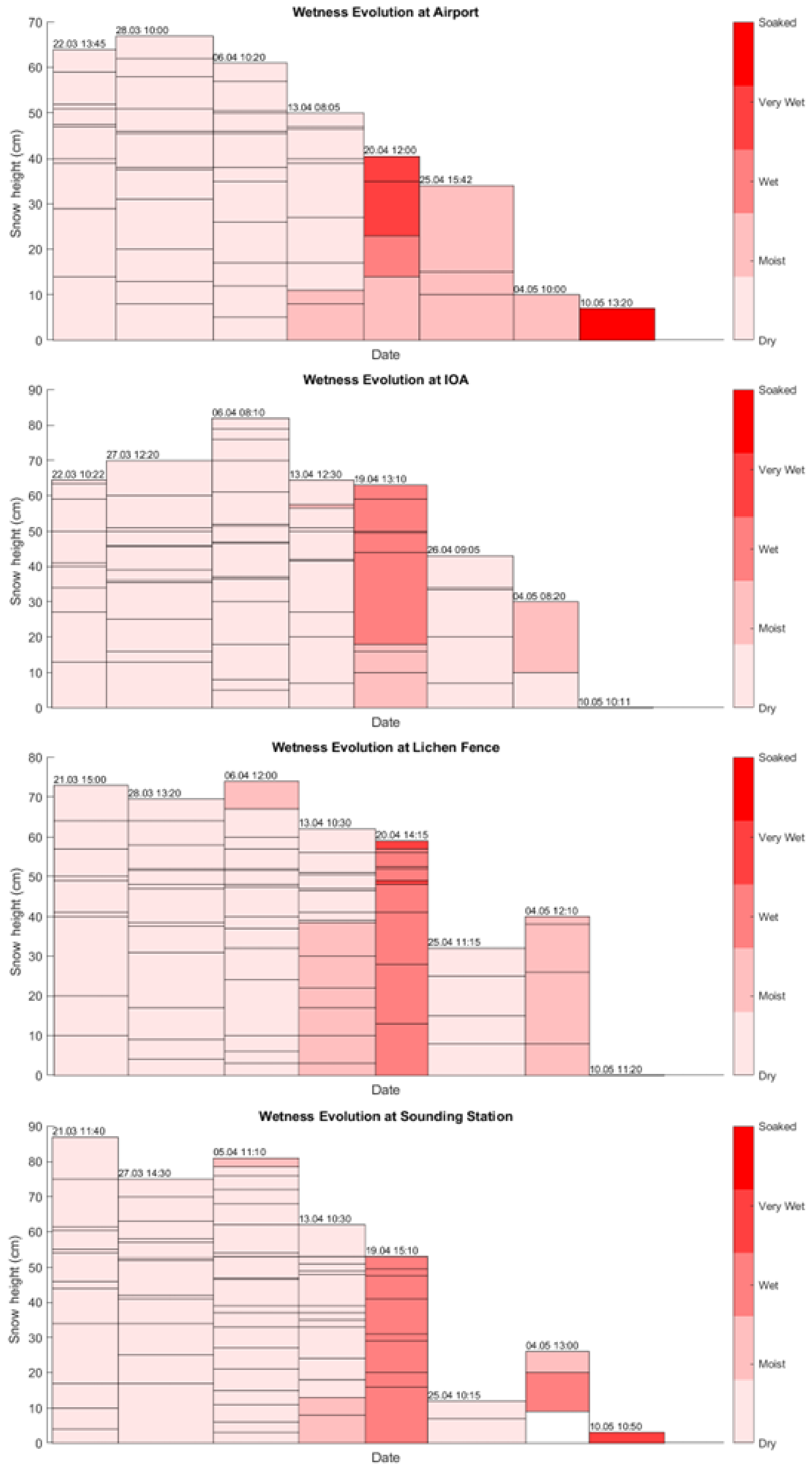

210 **Figure 6: Evolution of the wetness within the layers. The more reddish the color the wetter the snow.**

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4. Discussion

The study addressed the extent of spatial and temporal variability of taiga snowpack characteristics during melting period in spring. To address this, an extensive field campaign involving weekly measurements of snow height, stratigraphy, temperature, and density over an eight-week period from March to May was conducted in Sodankylä. The chosen four locations (Airport, IOA, Lichen Fence, and Sounding Station) captured a large variety of landscape features.

The automatically measured spatial variability of snow height is 7.4 cm or 9.7% which is lower than expected, if compared to the results of Komarov and Sturm (2023), who find an average spatial variability of 13 cm in snow height between a vegetated and a non-vegetated area in the taiga. According to the automated measurements (Fig. 3a), the snow in the forest site melts faster than at the Sounding Station or the open area. This disagrees with the manually made measurements and the literature (Hannula et al., 2016). In the manual measurements the snow height remains higher in the forest and the snow cover is longer continuous. Similar observations were made by Hannula et al. (2016).

While it was expected that the bulk density would be lower near to vegetation due to increased water fluxes leading to enhanced depth hoar formation (Royer et al., 2021), this trend was not evident in the measurements. A possible explanation could be the distance from trees. Even if the measurements were taken inside a forest, maybe the influence of vegetation is only observable on a smaller spatial scale, closer to single plants. According to Mazzotti et al. (2020) the correlation between canopy closure and snow height is stronger at small scales from 0 m to 5 m. The actual proximity between the measurement locations and the nearest trees likely exceeded this small-scale range. Unfortunately, the specific distances to the nearest trees were not recorded.

By averaging the density cutter measurement over snow height, a comparison bulk density was estimated. These two measurement methods probably provide a qualitatively similar behaving density curve, meaning that the fluctuation of density throughout the snowpack is comparable, yet the absolute density differs between methods. These presumably occur, because when using the SWE tube, snow is pushed to the side, as described in Kaasik et al. (2023). Thus, the density is systematically underestimated. On the other hand, using the density cutter can systematically overestimate the density, as some areas can be sampled several times, especially in the case of layers with high densities, where accurate sampling is harder. The densities measured with the density cutter show consistent curves across all four locations, whereas the tube measurement displays more noticeable deviations, as well as a strong outlier in the last week. It is possible that the measurement method with the tube, driven into the snow from above, becomes less accurate, when the snow wetness is increasing, while the density cutter has the advantage that large heterogeneity within the snow layer can be circumvented more easily by skillfully placing the cutter. This disadvantage of the SWE tube could be very pronounced especially at the end of the measurement period, with a lot of sunlight, high daytime temperatures and correspondingly very wet snow.

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Overall, a systematic error of 13% using the density cutter and 9% for the tube density measurement is considered, following the results from Kaasik et al. (2023) and Proksch et al. (2016). Profound density fluctuations were observed during the initial stages of melting and with increasing wetness the bulk density of the snowpack nearly doubled.

The temperature profiles of the snow pits showed the expected patterns, particularly a semicircular curve reflecting short-term changes in air temperature. This curve forms because the snow cools down at night, causing parts of it to freeze. This cooling effect moves downward through the snow layer, creating a gradient. During the day, solar radiation heats the upper layers of the snowpack from the surface downward. This process alters the temperature gradients within the snow, creating a semi-circular profile. The formation of the melt-freeze crust due to short-term temperature changes shows how sensitive the snowpack is to daily cycles. By the end of April, the snowpack temperature stabilized at 0 °C across all measurement locations, regardless of the time of day.

The near-surface melting process commenced on 19th April and was observed at all locations. This melting within the upper layers, caused by solar radiation, was not surprising and led to the snow pits, that were measured later in the day being wetter. It was expected that incoming shortwave radiation would melt the uppermost layers first, but the opposite was found, thawing started in the middle or lower layers first. This might be caused by evenly heated profiles at the end of the day, which refreeze partly during the night due to cold air and soil temperatures. This pattern could indicate that the reduction in wetness, or refreezing, is a top-down effect driven by cold nights, which do not penetrate the entire snow column. A week later, the results revealed dry layers where previously moist layers had been, demonstrating that snow can persist for an extended period in the phase between melting and freezing at an intrinsic temperature of around $T = 0$ ◦C. A more continuous observation of the wetness would have been useful to analyze this temporal evolution.

The identified systematic error range in the bulk density measurements highlight the challenges of accurately characterizing snowpack properties. Density errors may arise due to inaccurate placement of the cutter and potential holes or gaps in the cutter filling. Another source of error results from the lowest layers, which are often interspersed with vegetation, such as lichens. These errors can significantly affect the interpretation of snow density data. Besides that, when considering spatial variability within the density or wetness measurements and the potential reasons for heterogeneity, it is necessary to compare the times at which measurements were taken and the corresponding air temperature. For instance, measurements taken in the afternoon under sunny and warm weather conditions may result in early snow melting, leading to a higher density, whereas measurements in the early morning after a cold night cause crusts resulting in a higher density. Consequently, the wetness estimations are only snapshots once a week and cannot capture the entire melt-freeze process. Long-term measurement of wetness would be necessary for a comprehensive understanding of the process.

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5. Conclusions

This study explored the spatial and temporal variability of taiga snowpack characteristics during the spring melt period through an eight-week field campaign (March–May 2023) in Sodankylä, Finland. Measurements of snow height, stratigraphy, temperature, and density were conducted at four sites: Airport, IOA, Lichen Fence, and Sounding Station.

On average, the spatial variability of automatically measured snow height was 7.4 cm (9.7%). Manual measurements at IOA closely matched automatic data, while at the Sounding Station, manual values were slightly lower. For density, variability was greater between measurement techniques (SWE tube vs. density cutter) than between sites, with density increasing during melt due to melt-forms, melt-freeze crusts and ice layers.

Initially, the snowpack exhibited cold surface temperatures and a typical stratigraphy with depth hoar in the lower layers (up to 21.5% of snow height). The snowpack's sensitivity to daily temperature cycles was evident in the formation of melt-freeze crusts. Wetness appeared from mid-April, first in the middle layers, likely due to top-down refreezing during cold nights. Melting progressed from 19 April onward, leading to melt forms, reduced snow height, and increasingly wet layers, especially at the base. By late April to early May, the snowpack became isothermal (0°C throughout).

These findings underscore both temporal evolution and spatial heterogeneity of snow properties during the melting season. The detailed characterization of snowpack dynamics across different environmental and snow conditions is essential for improving our understanding of taiga snow and supports applications involving snow-climate interactions, hydrology, and remote sensing, particularly in relation to optical and microwave observations.

Data availability

Data is available with DOI https://doi.org/10.57707/fmi-b2share.49feab821c4049a9a9c43a61468668a5.

Competing interests

The authors declare that they have no conflict of interest.

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Author contributions

Conceptualization M.F., C.B. L.L., Data curation M.F., L.L., Formal analysis M.F., Investigation M.F., J.N., L.L., Methodology M.F., L.L., Supervision C.B., L.L, Visualization M.F., Writing – original draft M.F., L.L., Writing – review and editing L.L., M.F., C.B., J.N.

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