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Spatial and Temporal Variation of Bulk Snow Properties in North Boreal and Tundra Environments Based on Extensive Field Measurements

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Abstract

In this paper, an extensive dataset of snow *in situ* measurements, collected in support of airborne SAR-acquisitions in Sodankylä and Saariselkä test sites in northern Finland, is used to analyse the heterogeneity of bulk snow properties (snow depth, density and water equivalent) over different land cover types in northern taiga and tundra areas. In addition, the applicability of different spatial frequencies of snow sampling to estimate the true snow conditions is investigated. Overall, the highest variability in bulk snow properties was found over sparsely vegetated land cover groups, but the scale of variation was smaller in forested areas, as these areas exhibited a low correlation length in snow depth. This implies that more frequent measurements should be executed in forested (~ every < 5 m) than in open areas (~ every 7.5-12.5 m) to catch the true variability in snow depth. The results also indicated that the current spatial resolutions of space borne microwave radiometers and radars used for the remote retrieval of bulk snow properties are all well above the limit to fully describe the spatial variation of e.g. snow depth even in open areas. This conclusion supports the demand of research investigating high-resolution parameter retrieval in remote sensing of snow, e.g. using advanced SAR techniques.

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1 Introduction

Snow is a temporally and spatially variable component of global climate and hydrological systems. Due to its high reflectivity, insulation and water holding capacity, changes in snow cover are crucial, for example, in water supply forecasts, and in ecological, climatic, and meteorological studies (Vaughan et al., 2013). Accurate snow information is needed to succesfully parametrize the snow component in numerical weather prediction (NWP) models (de Rosnay et al., 2014). The on- and offset of the annual snow cover is also linked to the carbon balance in the northern latitudes via soil freezing and respiration processes (Grogan and Jonasson, 2006).

Several studies have reported explicit changes in snow cover extent (SCE) and snow cover duration (SCD) over both Northern Hemisphere and Arctic snow cover in recent decades (e.g. Brown and Mote, 2009; Brown and Robinson, 2011; Choi et al., 2010). Many of these studies show explicit decreasing trends in the snow cover extent (e.g. Brown et al., 2010; Derksen and Brown, 2012) but with differing responses during the winter and spring months and in North America and in Eurasia (Brown, 2000).

Snow properties have been succesfully measured via satellites over several decades. Although remote sensing (RS) methodologies themselves have changed little, the available imagery is very different. Significant improvements have been achieved in the resolution of the retrieved information (Nolin, 2010) and in our understanding of the snow cover as a part of the global climate system. However, as even in flat areas snow properties vary in a number of different scales (Derksen et al., 2010; Sturm and Benson, 2004), snow information retrieval via satellite RS remains challenging. Typically one has to trade off spatial resolution for better temporal resolution, and vice versa, while vegetation, topography, and later, simplified snow physics in retrieval algorithms introduce error into the end products (Foster et al., 2005). These uncertainties can significantly affect our understanding of the current snow cover changes and could lead to biased evaluation of global climate models and erroneous input to NWP models (Frei and Lee, 2010).

The lack of extensive ground data collected simultaneously with the RS data is often a limitation for further assessment and development of RS algorithms. Furthermore, sufficient resolution to describe the variation of different snow parameters is not always clear. At what scale can we measure accurately enough to catch the relevant snow characteristics and what, in general, is the effect of the scale on the interpreted output information? At the moment, the

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best resolution achieved in the observation of snow parameters by optical sensors is in order of 250-500 m (Hall et al., 2002; Notarnicola et al., 2013), whereas passive microwave radiometers are limited to resolutions of tens of kilometres. Using synthetic aperture radar (SAR), resolutions ranging from, for example, one meter (e.g. TerraSAR-X/TanDEM-X) up to 50 km (ENVISAT/ASAR) can be achieved (Dietz et al., 2013). However, the revisit times of space-borne radars are, even at best, typically limited to several days at high latitudes, whereas passive instruments, at the expense of resolution, can have daily coverage over a large part of the Northern Hemisphere (Dietz et al., 2013). Understanding the signal response within a 625 km^2 footprint produced by radiometers is challenging (Foster et al., 2005; Nolin, 2010). Microwave methodologies are generally practical for monitoring SWE and SD, whereas optical instruments are suitable for SCE and albedo measurements. The optical methods suffer from the lack of sufficient sun-light and frequent cloud cover in the northern latitudes (Warren, 1982).

In this paper, an extensive field measurement dataset acquired in Finland is used to quantify the temporal and spatial heterogeneity of different bulk snow parameters in the northern taiga and tundra environments. A large collection of *in situ* snow data was collected in support of ESA SnowSAR airborne acquisitions in Northern Finland during the winter of 2011-2012 (Lemmetyinen et al., 2014). During the measurement campaign, the mission concept of the proposed ESA CoReH2O (Cold Regions Hydrology High-resolution Observatory, ESA 2012; Rott et al., 2010) mission, at that time a candidate for the ESA Earth Explorer-7 satellite, was demonstrated. The main objectives of this study are 1) to characterize the temporal and spatial heterogeneity of bulk snow properties by calculation and comparison of land cover specific statistics of snow depth (SD), snow water equivalent (SWE), and snow density, 2) to investigate the temporal changes in snow stratigraphy over different types of land cover by description of snow stratigraphy changes, and 3) give an estimate of an optimal sample frequency for SD measurements by autocorrelation analysis and investigate the applicability of different sampling frequencies to estimate the true snow conditions.

2 Data and methods

2.1 Study sites

The *in situ* data used in this study were collected in support of ESA SnowSAR airborne acquisitions, which occurred over three sites during the winter of 2011-2012. Most acquisitions were located at the primary site, an approximately 7 by 10 km area close to the FMI Arctic Research Centre (FMI-ARC) located in Sodankylä northern Finland. Each airborne mission attempted to cover the entire area using a mosaic of up to 30 flight transects. Acquisitions were timed to correspond closely to the planned CoreH2O revisit times during the two proposed phases of the mission (3 and 15-day revisit time). The main site represents a typical boreal forest/taiga environment dominated by spruce/scots pine forests of varying density, as well as open peatbogs (wetlands) (Fig. 1 left). The elevation in the area varies between 180 m and 240 m above sea level and is relatively flat. The area covered by the acquisitions also included several rivers and lakes.

The second site was situated ~150 km north of the primary site in Saariselkä region (Fig. 1 right), representing an upland tundra environment. The area is mainly treeless, but the ground vegetation is characterized by lichen, mosses, sprigs and some larger shrubs, which result in a more varying distribution of snow cover due to wind effects. The general topography was also more variable with several low-lying tundra hills situated along the acquisition path. This site was visited twice during the season; a single ~20 km transect was covered. The aim was to provide data for CoReH2O retrieval performance testing over the tundra land cover type, which was not well represented at the main site. A third site of acquisitions was located over sea ice in the Gulf of Bothnia, but these data are not covered here.

2.2 Data collection

The airborne acquisitions were aimed to follow a 15-day repeat period between December and mid-February, corresponding to the repeat-pass time of CoReH2O during the second phase of the mission. For a period between February 22 and March 9, a three-day repeat period was planned, corresponding to the planned CoReH2O repeat pass time during the first phase of the mission (See dates in Table 1). A total of ten airborne acquisitions, as well as one dedicated calibration mission, were flown at the main site. Two acquisitions were flown at the Saariselkä tundra site. Ground sampling at the main site took place on most occasions during

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the day of the airborne acquisitions. On occasion, sampling was continued on the day following a flight, if the snow conditions remained stable. In Saariselkä, ground data was collected only on the dates of the airborne acquisitions.

Manual sampling of SD and SWE along flight transects formed the core of the *in situ* data collection in support of each SnowSAR acquisition. Figure 1 shows the locations of the collected ground measurements at the Sodankylä and the Saariselkä test sites. The basic concept was to, at minimum, cover at least two 5 km transects for each flight. Snow depth was sampled every 100 m while SWE was sampled every 500 m. As a goal, the sampling of designated tracks was designed to take place within 200 meters (across-track) from the planned centrelines of the flight transects. Sampling teams moved either on foot (snowshoes), by skis, or by snowmobiles. At each sampling site, snow depth was recorded at minimum from three representative locations in a 10 m radius, while the SWE measurement was taken from one representative location. An automated geolocated snow depth measuring tool (‘Magnaprobe’) was also used on all sampling days. For transects where the Magnaprobe was employed, SD measurements were considerably more frequent in distance (approximately every 2-10 meters).

On individual tracks, the measurements were conducted at approximately the same locations for every SnowSAR mission, to minimize the disturbance of the snowpack in the measurement area. The main objective of the distributed measurements was to obtain a maximal amount of SD/SWE samples for comparison with the airborne observations. Around 600 SWE, 22 100 SD measurements were collected during a total of 19 days between December 2011 and March 2012 (Table 1). Additionally, the manual snow measurement program of FMI-ARC provided snow pit observations at three sites in the Sodankylä area, enabling to construct a time series of the physical evolution of snow over dry mineral soil, wetlands and lake ice during the campaign (Leppänen et al., 2015).

2.3 Data analysis

2.3.1 Data processing and analysis of snow heterogeneity

Erroneous data points (e.g. snow depths smaller than 1 cm) and duplicates were removed from the dataset. Based on GPS coordinates, for each measurement point, land cover class was determined. The land cover information was available through the European Commission programme to COoRdinate INformation on the Environment (Corine). An updated dataset

(CLC2012) was used. Analogously to former airborne data analysis from the site (Lemmetyinen et al., 2015) the original 44 CLC2012 land cover classes were generalized into nine land cover groups (Table 2). The spatial coverages of different land cover groups within a 7 km x 10 km area in the both test sites, used later in the analysis, are also shown. Forested areas were divided based on both the tree canopy closure (>30 % dense/ <30% sparse) and the soil type (mineral/peat or organic). Different types of open areas were also separated (wetlands, meadows, barren surfaces, water systems). The ninth group included all artificial surfaces, such as roads and buildings, and were excluded from the analysis.

The division of the measurements based on canopy closure as well as the overall land cover class is justifiable because canopy closure has been observed to be one of the main factors to affect snow accumulation (e.g. Dobre et al., 2012; Storck et al., 2002). This applies especially to flat areas, such as the Sodankylä region, where elevation and aspect have little effect (D'Eon 2004). In addition, RS of snow cover has proven to be problematic in forested regions (e.g. Foster et al., 2005; Heinilä et al., 2014). In the boreal forest zone, the vegetation itself has large effect on the RS measurements and needs to be taken into account (Cohen et al., 2015; Derksen, 2008; Metsämäki et al., 2012) whereas in tundra regions the high proportion of frozen lakes, local scale variability due to wind effects, and stratigraphically complicated snowpack introduces different kinds of problems (Derksen et al., 2010).

Density information for each snow depth measurement point was determined based on the distributed SWE measurements. Since fewer SWE than SD measurements were available, the density was calculated per day per land cover group. If more than one SWE points were measured within the same land cover group during the same day, an average of these measurements was used. In case no density information for a distinct land cover group was available, data from the previous or the subsequent measurement day was used, if no precipitation events or drastic temperature changes had occurred. The variation of air temperature and the daily precipitation amount at FMI-ARC in Sodankylä during the measurement campaign are shown in Fig. 2. After the density determination, SWE for each SD data point was calculated. For some data points no density and thus SWE information could be determined. The number of SD and SWE measurements within each generalized land cover group during each measurement day is represented in Table 1. Finally, a boxplot for each land cover group for each measurement day was created to describe the temporal variation in the snow properties during the measurement campaign.

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The evolution of snow physical properties (grain size, density, stratigraphy, and temperature) was analysed from snow pit information collected from three sites (sparse forest on dry mineral soil (SFm), wetland (OB), and lake ice (LR)).

2.3.2 Autocorrelation of snow depth measurements

The statistical variability of SD over different types of land cover was investigated by means of analysing the autocorrelation of measured SD values over distance. Snow depths measured with the Magnaprobe instrument were applied, as these provided the necessary high spatial sampling frequency. The goal was to estimate the optimal sampling frequency for snow cover in different land cover conditions, informing future planning of snow sampling campaigns in the region, and to identify deficiencies of the relatively sparse sampling approach applied elsewhere during the campaign (SD every 100 meters, SWE every 500 meters).

In order to harmonize the analysis, multiple transects of 500 meters were chosen from the collected data, representing each investigated land cover group. Autocorrelation was calculated as a function of lag distance. An exponential fit was applied to the autocorrelation, deriving the exponential (auto) correlation length (L_{ex}). However, the data did not cover all land cover groups for all SnowSAR acquisitions with a sufficient amount of samples to conduct the autocorrelation analysis. The autocorrelation analysis was applied only for SD as SWE was estimated for each SD measurement point via land cover type fixed density and would have produced same results as the previous analysis.

2.3.3 Effect of sampling frequency

To further investigate the effect of sampling frequency, the average SD obtained via the frequently executed Magnaprobe measurements and, the more sparsely executed measurements with a snow ruler (henceforth called conventional SD measurements), were statistically compared. The goal was to assess if the different sampling frequencies (Magnaprobe, potential over-sampling / conventional, potential under-sampling) lead to a statistically significant difference in the mean SD. Three land cover groups (DFm/OB/LR), characterized by different average SD, and measurement days comprising a sufficient amount of both Magnaprobe and conventional measurements were chosen for the comparison.

For the analysis, each sub-group of the measurements was tested for normality by histograms and by the Kolmogorov-Smirnov test for later selection of appropriate statistical analysis. For part of the groups the assumption of normality did not hold. The equality of variances between the groups was tested as well by executing both the Levene's and the Bartlett's tests. If the test results were inconsistent, the histograms were investigated to assess, which result could hold better. As the assumption of equal variances also did not hold between all the compared groups, and the sample sizes varied, finally, both the Welsch's t-test for unequal variances (assumes normality but not equal variances) as well as the Mann-Whitney U-test (MWU) (assumes equal variances but not normality) were chosen to test the statistical difference of means.

Furthermore, as *in situ* data is often averaged over the field of view of RS observations for validation purposes, it was investigated, if different measurement frequencies lead into different outcomes when a weighted average, based on land cover proportions within a typical RS observation grid cell, is calculated. For this purpose a 7 km x 10 km area was cut out from the generalized CLC2012 land cover data and percentual coverages of each generalized land cover group, both in the Sodankylä and in the Saariselkä test sites, were determined (Table 2). This area was approximately equivalent to the spatial extent of the ground measurements in the Sodankylä test site. In the Saariselkä test site, the ground sampling occurred on a slightly smaller area, but for the comparison purposes, areas of same sizes were chosen. Four campaign days with a high amount of measurements were chosen for the analysis; three days from the Sodankylä test site and one day from the Saariselkä test site, as enough measurements were available from Saariselkä only from the second acquisition day. The distances between all the consequent measurements were calculated and three different cases of measurement frequencies were compiled; one with maximum sampling frequency (~ every 1-10 m), one with medium sampling frequency (~ every 100 m), and one with sparse sampling frequency (~ every 500 m). However, as the measurement distances varied and were not always exactly e.g. every 100 m, it was not possible to produce withholded data with the exact sampling frequencies; the sampling frequencies, for example, in the 100 m case may actually vary between ~70-150 m. However, the sampling frequencies of the three cases were still clearly different. A proportionally weighted average for both SD and SWE were calculated separately for each case of measurement frequency.

3 Results

3.1 Land cover specific variation of snow properties

The median SD of the lakes and rivers was distinctly lower than those of the other surface type groups during the whole measurement campaign (Fig. 3). The deviation of snow depth in the lakes and rivers was also generally lower (or during few days, as high as) the deviation in the other land cover groups. An exception occurs in the beginning of March when comparatively high deviation in the measured SD was seen. One possible explanation for this is that in the beginning of March, most of the measurements were taken on river ice whereas during the other days the measurements were mainly on lake ice. The narrow creeks might have larger SD variation than open lakes. Another possible reason is the imprecision in retrieving the CLC2012 data for the measurement points. The resolution of the CLC2012 is 20 m and the handheld GPS devices used during the ground data collection may have inaccuracies of several meters. This could have led to an incorrect classification of, for example, adjacent forest measurements as lake and river measurements in the narrow creek areas.

Another distinctive group was the open bogs, also with lower median SD values. The difference between the open bogs and the other groups was more significant in the beginning and in the end of the measurement campaign than in the middle. In the forest groups, the median SD of the dense forests on mineral soil was lower than the median SD of the dense forests on peat soil during most of the campaign period. One possible explanation for this could be a different canopy structure in the forests on mineral and peat/organic soils. The relationship between the sparse forests on mineral and peat soils was similar, but the differences in the median SD were smaller and the relationship was not as clear as between the dense forest groups. The median SD of the fields and meadows and the barren land were not clearly lower or higher than that of the forest groups (DFm/DFp/SFm/SFp). Overall the median SD of the fields and meadows and the barren land cover groups was slightly lower than the median SD in the forest cover groups and a bit higher than that on the open bogs. The highest deviation in SD was measured during the Saariselkä measurement day (29Feb). This indicates well the effect of elevation changes and wind on the SD variation on open tundra site in relation to the taiga forest site in Sodankylä. Regarding the median and deviation of the SWE measurements in the different land cover groups (Fig. 4), very much similar results than with the SD values were obtained, but the differences, for example, between the two dense and sparse forest groups were slightly easier to detect.

For the density calculations fewer measurements were available and on some days a single measurement might represent the snow density value in a land cover group (Fig. 5). The median density was highest in the field and meadows and the barren lands measured in the Saariselkä test site. This is explained by the wind effect which packs the snow and easily introduces larger densities than in the taiga test site. The effect of wind and elevation changes were also seen in the high deviation in the measurements made in February 29th. The deviation of snow density on the lakes and rivers was very large when looking both the median density values and the difference between the minimum and the maximum values; on some days, the density of this group was lower, and on some days much higher than in any other land cover group. The wind also played a role in the open water areas but probably even more, the high density variation was related to water which might rise to the ice surface on mild air temperatures. The comparatively thin snow layer also thaws easily during warm days in spring. For the density values, the relationship between the values of the land cover groups was different from those of SD and SWE, as densities were typically higher in the open areas than in the forested areas. The relationship between the different forested land cover groups was not clear, the dense forests on mineral soil exhibited lower densities than the other forested land cover groups. It was also notable that the variation in density between the different land cover groups did not stay constant but as environmental factors changed, snow bulk density in the different land cover groups reacted differently; on some days all the measured densities of the land cover groups were very close to each other, and on other days large differences existed.

The evolution of snow stratigraphy over dry mineral soil, wetlands and lake ice during the campaign are depicted in Fig. 6. Snow structure evolved from December to March by addition of new fine-grained snow layers on the surface (deep blue in the Fig. 6) and grain growth in the lower half of the snowpack (from light blue through green and yellow to orange). These effects were also visible in the snow density profiles: new snow on the surface was very light, and the density of the bottom layers increased throughout the winter. Snow structure in the forest on mineral soil and over the open bog was very similar, at least compared to snow on the lake ice; similar layers could be detected from the forest and the open bog profiles, even though from different heights. Typically snow depth on the bog was smaller than in the forest,

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but the heavy snowfall in February (between 8 and 22 Feb) evened out the difference. Temperature profiles reflect the fact that air temperature was the same at all pits measured on the same day; the differences in the snow surface temperatures can be explained by the differing measurement times. The disparity between the temperature profiles in e.g. 9 Jan is due to differing snow depths.

3.2 Analysis of snow depth autocorrelation

The autocorrelation of the measured SD values over distance was analysed to statistically describe the variability of SD. Examples of the autocorrelation of the measured SD over representative transects are shown in Fig. 7 for the forested areas (DFm) and the wetlands (OB). An exponential fit to the autocorrelation is shown. The correlation length (in meters) derived from the fit is also displayed, providing a measure of the degree of variability in snow depth over distance. The forested sample exhibited the lowest L_{ex}, while autocorrelation remained high over longer distances over the wetland transect.

The mean and standard deviation of L_{ex}, derived for the different land cover groups, is summarized in Table 3. The values were calculated from representative 500 m transects selected from all Magnaprobe sampling campaigns at the main site, as well as the second Saariselkä campaign. The barren land cover type represents data collected from the second Saariselkä campaign (average and standard deviation of L_{ex} from 21 transects), while only one suitable transect was available from the main site representing the sparse forests on peat soil. On average, the forested areas exhibited a low correlation length in snow depth, while values collected over lake ice and wetlands exhibited correlation lengths in excess of 15 meters. Over the barren landscape in Saariselkä, the average autocorrelation was in excess of 20 meters. This can be explained by the influence of the forest canopy, which affected the spatial distribution of snow accumulation on the forest floor, inducing a large variability over short distances. However, when the mean coefficient of variation (CV) for each land cover group, representing the whole campaign period, was calculated (Table 4), the dispersion of SD was highest on the lakes and rivers and on the barren lands and remained low in the forested land cover groups and on the fields and meadows.

3.3 Effect of sampling frequencies

The results from the statistical analysis of the difference of means in SD are represented in Table 5. Both of the statistical tests gave similar results when the means of frequent Magnaprobe measurements and the sparse conventional measurements were compared. Only on 26Feb in the dense forests on mineral soil the Welch's test estimated the difference to be significant whereas MWU-test estimated it insignificant (at a 0.05 level of confidence). During most of the days, difference of SD means was significant in the dense forests on mineral soil. This supports the result of the autocorrelation analysis, where snow depth varied in short distances due to e.g. forest canopy effects. Two days with measurements from the lakes and rivers were analysed and during both days the difference in SD means was statistically significant. The results from the comparisons of the open bogs were not consistent; during the first two days compared, the results were not statistically significant but during rest of the days, they were.

The weighted averages of SD and SWE for the 7 km x 10 km areas are presented in Table 6. A consistent effect of the measurement frequency could not be determined; during the first two days investigated, the weighted averages increased slightly as the sampling frequency was decreased. However, during the second last day investigated (23Feb), the weighted SD and SWE values decreased slightly between the most frequent and the 100m sampling case. The 500m sampling case did not introduce change in these average values. In the Saariselkä test site (29Feb), the differences between the three cases of sampling frequency were larger and were first decreasing and then increasing along the sparser measurement frequency. The last two dates had the most frequently measured snow parameters and the measurement frequency could be most accurately manipulated. Overall, the averaged SWE values changed more along with the sampling frequency than the values of SD. As SWE values were retrieved by using the land cover specific density values, an additional source of error in the frequent SWE dataset existed. For any robust conclusion, a more comprehensive analysis of the effects of the sampling frequency needs to be done with a dataset, in which frequency changes are optimised for this kind of study.

4 Discussion

There are three often-mentioned generalizations about the spatial variability of snow. According to the first one, seasonal snowpacks are more heterogeneous than perennial snowpacks due to higher amount of acting agents (Sturm and Benson, 2004). In addition to wind and water percolation effects, vegetation and topographic changes affect seasonal snowpacks whereas in perennial snow, the first two factors are the most important. Secondly, it is generally thought that snow is less spatially variable in forested than in open areas (in arctic and subarctic), as in open areas the wind redistribution effectively increases the heterogeneity (Derksen et al., 2014; Essery and Pomeroy, 2004). Thirdly, slightly contradictory to the second generalization, variation of SD and SWE is often thought to be higher in forested areas, where complicated canopy structure affects the snow accumulation on the ground, than, for example, in open areas (Dobre et al., 2012; Storck et al., 2002). In this study, the heterogeneity of bulk snow properties (SD, density and SWE) was analysed from three different perspectives; by statistical description of bulk snow properties in different land cover groups, by autocorrelation analysis (for SD only), and by the determination of an averaged CV for each land cover group investigated.

According to the statistical description of bulk snow properties (e.g. Fig. 3 and 4), deviations in snow depth between the land cover groups were often small, being in the order of 1-3 cm. In addition, the relative differences did not remain constant (e.g. deviation in the forested areas was not always higher than in the open areas), but varied even during the mid-winter. Only the bulk snow properties measured at the Saariselkä test site had consistently higher deviations in the measured values of SD, density and SWE than the values at the main test site in Sodankylä. This supports the earlier results of the variation of snow properties over tundra (e.g. Derksen et al., 2014). However, the autocorrelation analysis presented in the Sect. 3.1.2, revealed that the snow properties tended to vary more on short distances in forests, although, on average the deviation in forests was no higher than over sparsely vegetated land cover groups. This supports the third generalization mentioned in the previous section. Lastly, the mean values of CV revealed an opposite phenomenon as the lowest CV values were observed in the forested land cover groups (Table 4). This implies that although the absolute variation in snow depth was largest in the sparsely vegetated groups, this heterogeneity appeared on scales larger than that in the forested groups. By analysing the autocorrelation of measured SD values over distance in different land cover groups, the proper sampling frequency capturing the true variation in the measured quantity, can be determined. The L_{ex} averages for the different land cover groups shown in Table 3 indicated that in open areas a measurement frequency of 7.5-12.5 m for SD was adequate. Ideally, the sampling should be executed at least twice more frequently than L_{ex} so that the true variance could be captured. In forested areas, the snow depth should be measured every < 5 m to catch the true variation of SD. These results, however, show that the sampling frequency used usually in the conventional snow course measurements (e.g. SD every 50 m, SWE every 500 m for Finnish Environment Institute snow course measurements) is not optimal for the full spatial description of SD. Explicit improvement in the data quality could be achieved by following the presented measurement guidelines for the spatial sampling frequency. With respect to RS applications, instruments measuring at resolutions higher than the land cover group specific L_{ex} do not provide meaningful statistical information compared to instruments whose resolutions are close to the values of L_{ex}.

The need for higher sampling frequency in the forested areas was supported by the analysis presented in the Sect. 3.1.3, where with only one exception, the difference in mean SD obtained via the Magnaprobe and the conventional measurements, was statistically significant in the dense forests on mineral soil. On the lakes and rivers the differences were also statistically significant during the both days investigated. This could be related to the overall high variation of SD on lakes and rivers (Table 4). On the open bogs, the differences became statistically significant towards the end of the campaign with increasing snow depth. It is hypothesized that this is because the overall deviation in SD tends to increase along with snow depth, and as such, different sampling frequencies might have more effect.

The variation of all bulk snow parameters at the Saariselkä test site was very high. This indicates that retrieval of snow parameters in a tundra region with only mild elevation changes (highest fells were usually around 500 m), and where the vegetation effect is almost non-existent, can still be very complex. Furthermore, factors such as aspect and elevation, which were not considered in this study, should be taken into account. The effect of different sampling frequencies on the spatially averaged values of SD and SWE was not clear (Table 6). The analysis gives some robust references that the effect might be more significant in SWE than in SD measurements and that the effect increased as the SD increased along the snow season. One could also hypothesize that the sampling frequency might affect more in the tundra site, as the bulk snow property variation in tundra is generally very high and the obtained differences in this analysis were larger than the ones obtained in the Sodankylä test site. However, a more sophisticated analysis needs to be done to properly evaluate the effect of different sampling frequencies on the spatially averaged bulk snow property values, which are often used for RS data validation purposes.

The temporal changes in snow stratigraphy in the different types of land cover (Fig. 6) revealed that the evolution was rather similar between the sparse forest on mineral soil and on the open bog; the main differences were seen in the bottom of the snowpack where the local microtopography can significantly increase the spatial and temporal heterogeneity of the snowpacks (Sturm and Benson, 2004). The snowpack stratigraphy on the lake ice was very different from the other two snowpacks with lower SD and fewer snow layers.

5 Conclusions

In this study an extensive dataset of *in situ* snow measurement, collected in support of ESA SnowSAR airborne acquisitions in Northern Finland during the winter of 2011-2012, was used to describe the temporal and spatial heterogeneity of bulk snow properties in different types of land cover in tundra and taiga test sites. The optimal sampling frequency for SD measurements was investigated by means of an autocorrelation analysis of measurements with a high sampling rate. The applicability of different sampling frequencies to estimate the true snow conditions was analysed. This can also be useful to inform the development of RS methodologies, as the spatial and temporal heterogeneity of snow is one of the main challenges for correct RS information retrieval.

The results revealed that although, on average, the deviation of bulk snow properties in the forest land cover groups was not higher than in the open land cover groups, snow properties tended to vary more over short distances in forests. On the other hand, the absolute variance, described by the averaged coefficient of variation for each land cover group, showed the highest dispersion of the measurement values in the open land cover groups. This indicates that although the absolute variance in forests was lower than in the other groups, more frequent sampling procedure should be applied to fully catch the bulk snow property variation in the forested types of land cover. A measurement frequency of 7.5-12.5 m is adequate in open bogs and lakes and rivers. In forested areas the snow depth should be measured around every < 5 m to catch the true variation of SD.

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With respect to remote sensing applications, the results showed that the current spatial resolutions of the space borne radiometers and radars used for remote SD retrievals are all well above the limit to fully describe the spatial variation of snow depth even in open areas. The conclusion supports the demand of research investigating high-resolution parameter retrieval in RS of snow, e.g. using advanced SAR techniques.

In the future work this extensive snow ground dataset will be further analysed and utilized together with simultaneously observed airborne and space-borne RS observations, with the goal of developing novel retrieval algorithms for snow geophysical properties.

Acknowledgements

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Table 1: The *in situ* measurement dates, the number of snow depth and SWE/density measurements, and the snow pit observations (* + Mar13) in the different generalized land cover groups. Dates marked in **bold** indicate measurements days conducted in the Saariselkä test site.

Land cover group	Dec 19	**Dec 20**	Jan 9	Jan 10	Jan 23	Jan 24	Feb 7	Feb 8	Feb 9	Feb 22	Feb 23	Feb 24	Feb 25	Feb 26	**Feb 29**	Mar 1	Mar 5	Mar 8	Mar 23	Total
	SD SWE																			
DFm	91	x	195	x	172	218	86	20	17	587	1018	177	658	116	11	1238	22	58	23	4887
	4	x	4	x	7	8	7	6	3	13	13	1	1	12	x	16	7	6	5	113
DFp	30	x	25	x	24	72	23	23	5	193	209	98	58	55	x	134	7	41	11	1008
	3	x	5	x	2	4	1	2	2	4	4	x	x	2	x	1	2	1	3	36
SFm*	95*	x	3*	x	74	81	22*	45*	13	241*	126	53	44	32	16	179	15	36*	13*	1120
	4	x	2	x	4	2	1	2	4	6	2	x	x	4	x	6	2	4	3	46
SFp	19	x	46	x	17	38	34	11	3	141	92	78	73	63	x	201	8	53	7	884
	1	x	2	x	2	2	3	1	x	4	1	2	1	5	x	4	5	3	1	37
FM	17	11	35	x	37	7	37	28	x	138	146	7	10	45	3154	111	x	x	5	3788
	x	3	1	x	2	2	1	4	x	10	x	1	1	1	60	3	x	x	x	89
B	x	5	x	x	2	x	x	2	x	x	x	x	x	x	588	x	x	x	x	597
	x	1	x	x	x	x	x	x	x	x	x	x	x	x	11	x	x	x	x	12
OB*	331*	x	333*	262	123	69	281	55*	45	598*	407	791	2761	380	x	1052	60	300*	92*	7940
	14	x	25	7	23	5	11	5	9	27	8	8	13	23	x	23	9	18	20	248
LR*	x*	x	42*	x	375	3	32	254*	1*	1098*	1	x	x	x	x	6	4	10	57*	1883
	x	x	1	x	10	x	2	10	1	8	1	x	x	x	x	1	1	2	4	41

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Table 2: Generalization of the field measurements based on the CLC2012 land cover classes analogously to Lemmetyinen et al. (2015), and the spatial coverage (%) of each land cover group within a 7 km x 10 km area in the Sodankylä and the Saariselkä test sites.

Acronym for generalized land cover group	Description	CLC2012 classes	7x10 km area coverage (%)	
			Sodankylä	Saariselkä
DFm	Dense forests (mineral soil type)	22,24,26,27,29	33.37	30.80
DFp	Dense forests (organic/peat soil type)	23,25,28	10.06	0.72
SFm	Sparse forests (mineral soil type)	33,35,36	7.85	5.32
SFp	Sparse forests (organic/peat soil type)	34	6.08	0.28
FM	Fields and meadows	16,17,18,19,20,21,30,31,32	4.84	50.40
B	Barren	37,38,39	0.02	10.94
OB	Open Bogs	40,41,42,44,45	25.68	1.22
LR	Lakes and rivers	46,47,(48)	10.81	0.06
O	Other (roads and urban areas)	1-15,43	1.29	0.25

Table 3: The mean and standard deviation of exponential autocorrelation length (L_{ex}) of snow depth over the land cover groups, calculated from representative transects during the snow sampling campaigns between Dec 19, 2011 and March 23, 2012.

	land cover class	DFp	DFm	SFp	SFm	OB	FM	B	LR
L_{ex}	mean	6.8	5.6	4.0	1.5	15.5	9.2	21.1	15.8
	stdev	3.6	1.9	-	0.7	7.8	6.2	15.0	5.3

Table 4. The averaged coefficient of variation for snow depth within each land cover group during the measurement campaign.

Land cover group	Coefficient of variation SD
DFm	0.16
DFp	0.13
SFm	0.13
SFp	0.13
FM	0.17
B	0.33
OB	0.20
LR	0.36

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Table 5: The statistical difference of means between the Magnaprobe and the conventional measurements within the dense forests on mineral soil, the open bogs, and the lakes and rivers. The p-value is marked with * if the result is statistically significant at a significance level of 0.05. The test type considered more appropriate for each individual group is marked in **bold**.

Date	Land cover class	n		Mean		Welch's t-test			Mann-Whitney U		
		Magna	conv	Magna	conv	Df	t-statistic	p	Df	MWU-statistic	p
19Dec	DFm	71	20	28.43	32.30	29.16	2.596	0.014*	89	445.5	**0.011***
	OB	233	98	23.00	22.99	225.34	-0.021	**0.983**	329	9993.0	0.073
23Jan	DFm	151	21	46.37	50.30	25.55	2.547	0.017*	170	1000.0	**0.006***
	LR	305	70	18.52	21.72	88.19	3.031	**0.003***	373	8224.0	0.003*
Jan24	DFm	191	27	44.84	47.97	34.04	2.188	0.036*	216	1841.5	**0.016***
	OB	46	23	46.21	41.70	34.97	-2.068	0.046	67	372.0	**0.046**
7Feb	DFm	54	32	48.54	53.84	68.85	3.730	0.000*	84	457.0	**0.000***
	OB	209	72	48.23	45.22	105.87	-2.506	0.014*	279	5563.0	**0.001***
8Feb	DFm	129	71	45.62	51.64	179.14	5.524	**0.000***	198	2545.5	0.000*
	LR	173	81	19.65	22.14	153.93	4.559	**0.000***	252	4561.0	**0.000***
22Feb	DFm	550	37	69.48	70.71	48.99	1.065	**0.292**	585	9742.5	0.665
	OB	446	152	66.10	57.38	291.35	-8.591	**0.000***	596	19659.5	0.000*
26Feb	DFM	94	22	65.21	69.44	53.18	2.284	**0.026***	114	828.0	**0.148**
	OB	308	72	57.38	50.86	120.08	-5.317	**0.000***	378	6883.0	**0.000***

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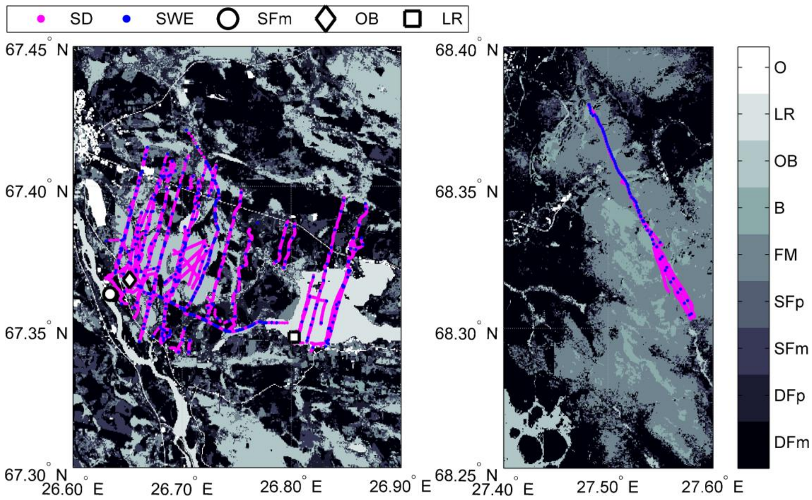
Table 6: The proportionally weighted averages (WA) of SD and SWE for the 7 km x 10 km land areas in the Sodankylä and the *Saariselkä* test sites for the three different cases of measurement frequency.

	SD			**SWE**		
	Magnaprobe WA	100 m WA	500 m WA	Magnaprobe WA	100 m WA	500 m WA
19Dec	25.07	25.05	25.35	50.13	52.62	52.89
23Jan	38.50	40.48	43.01	67.40	76.41	84.06
23Feb	68.82	66.65	66.62	133.74	129.73	129.73
29Feb	50.06	40.74	47.45	135.91	110.33	129.43

574 

575 Figure 1: Snow depth, SWE, and snowpit measurements (three different sites) collected in the
576 Sodankylä (left) and the Saariselkä (right) test sites during the SnowSAR acquisitions.

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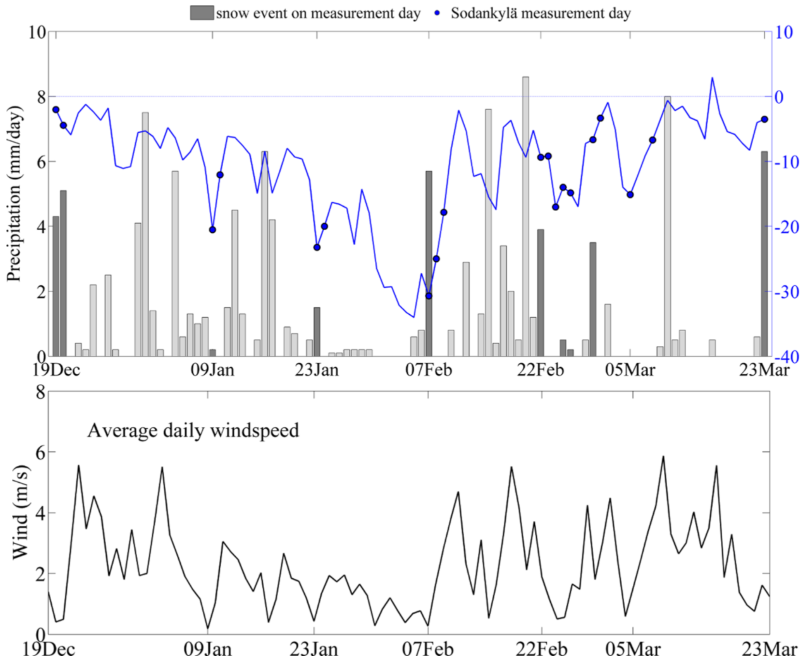

577 Figure 2: Daily average temperature, daily precipitation sum, and average daily wind speed during
578 and between the different field measurement days observed by the automatic weather station at
579 FMI-ARC.

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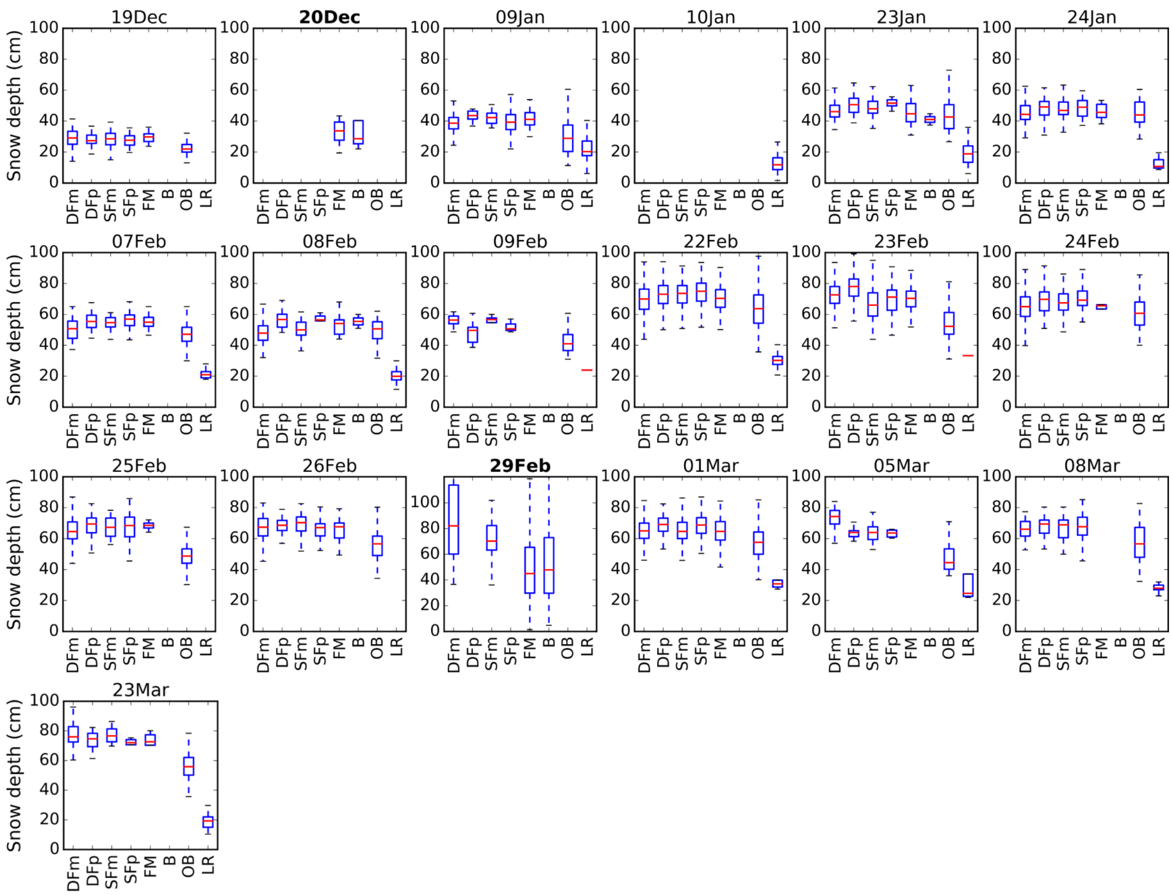

Figure 3: The boxplots of measured snow depth within each land cover group during the different field measurement days. Measurement days conducted in the Saariselkä test site are indicated in **bold**.

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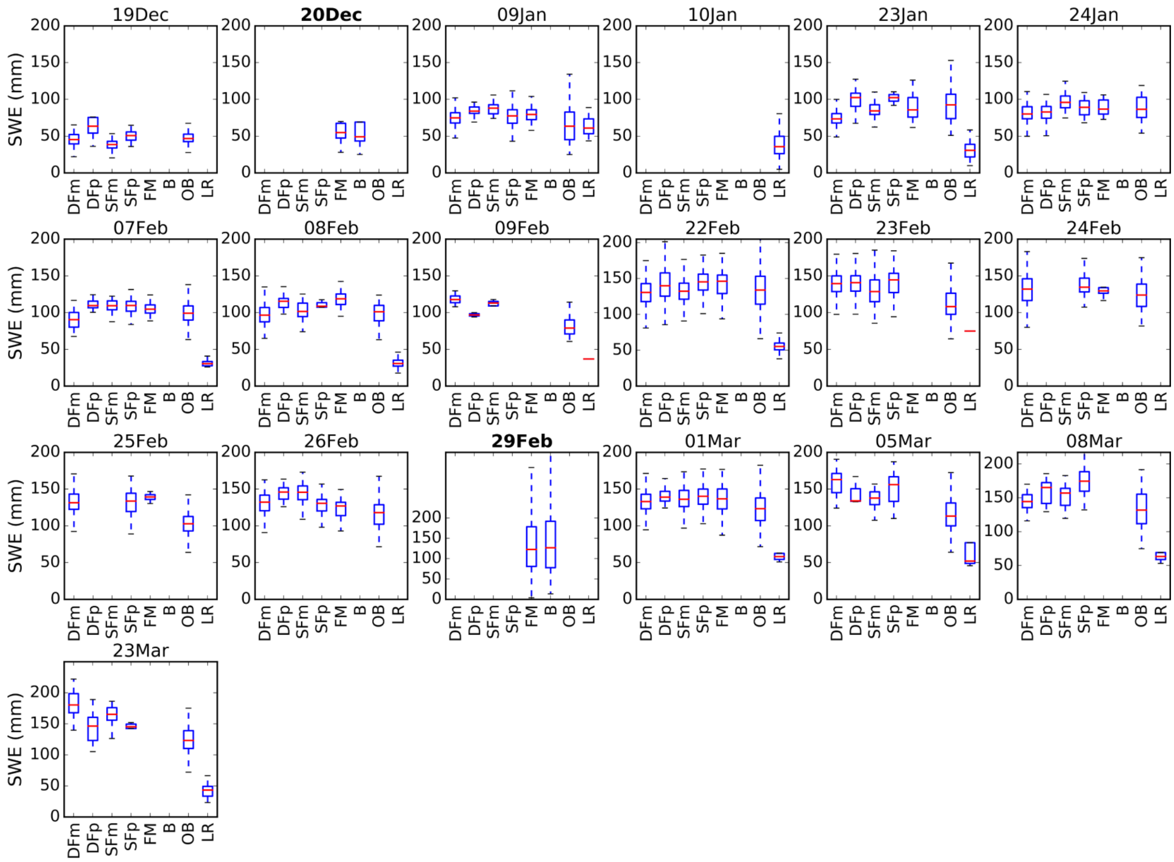

583 Figure 4: The boxplots of measured SWE within each land cover group during the different field
584 measurement days. Measurement days conducted in the Saariselkä test site are indicated in **bold**.

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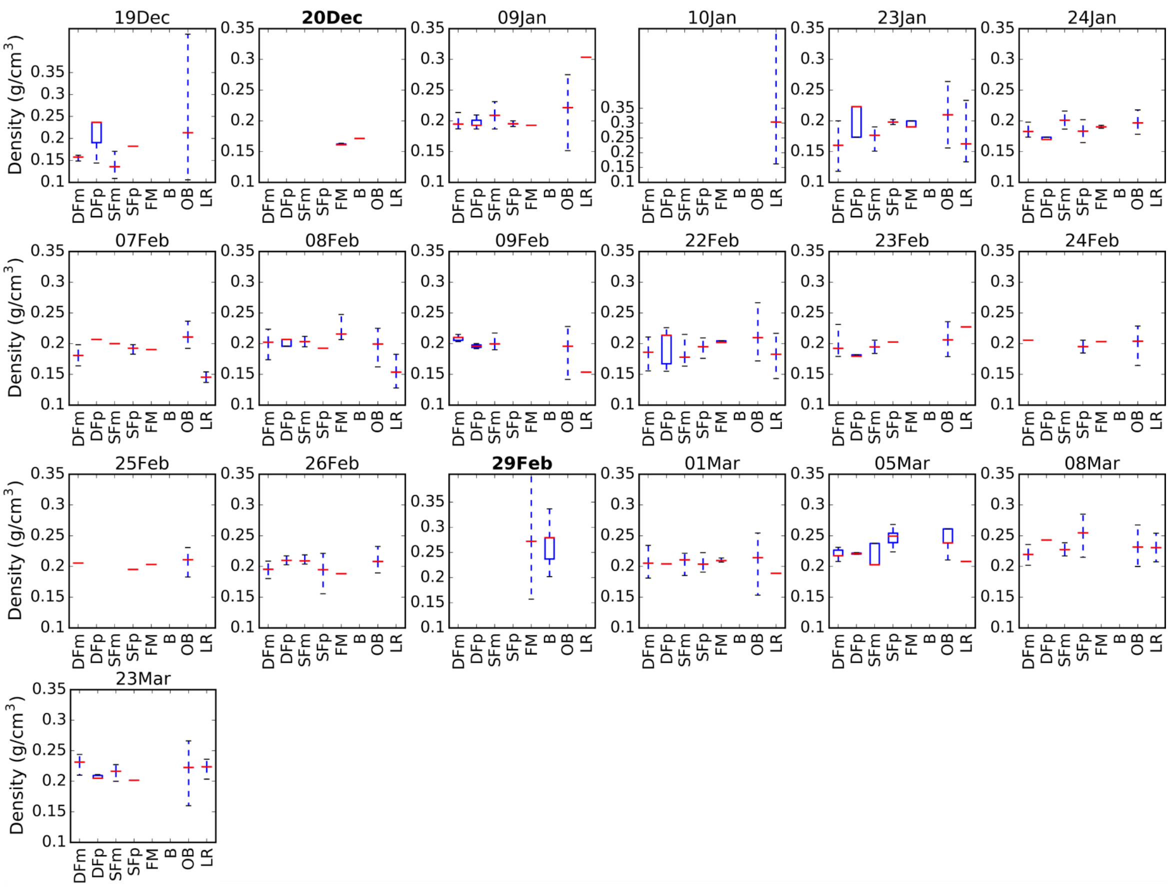

585 Figure 5: The boxplots of measured snow density within each land cover group during the different
586 field measurement days. Measurement days conducted in the Saariselkä test site are indicated in
587 **bold**.

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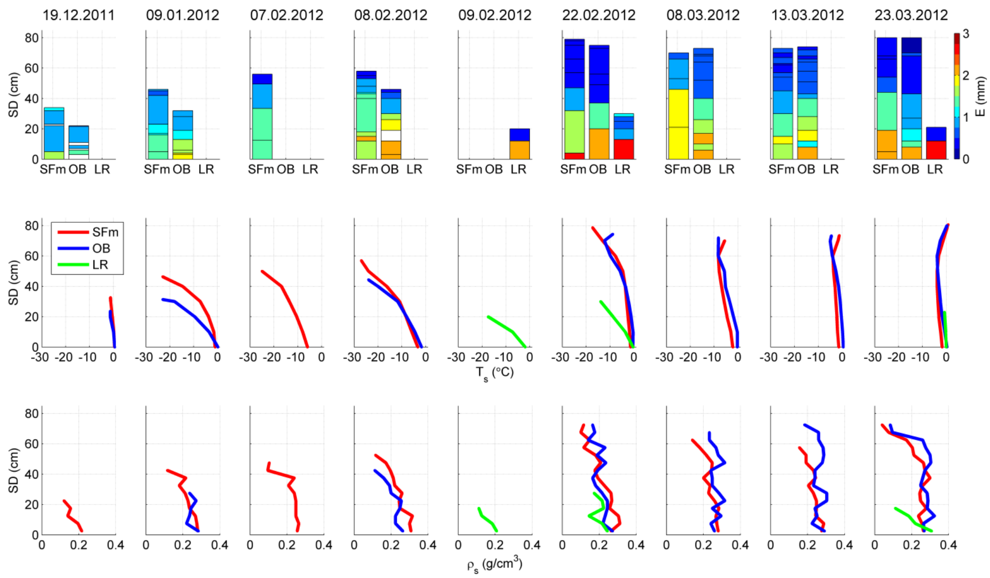
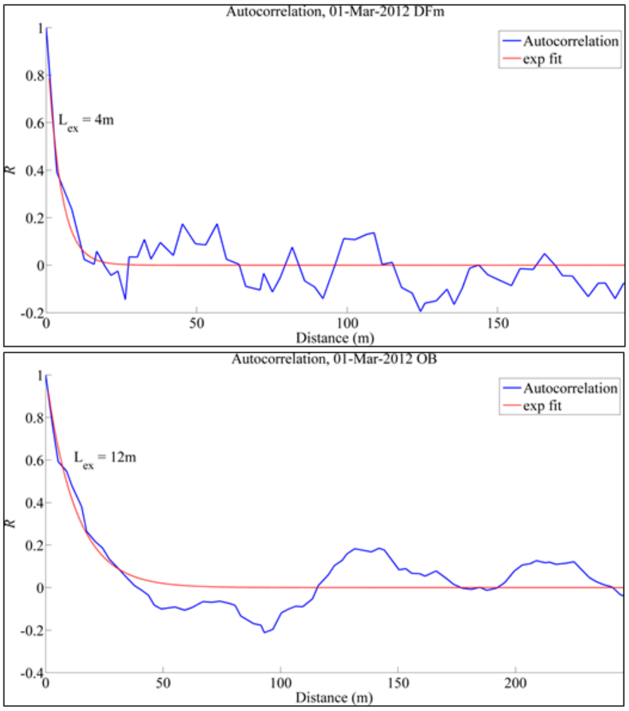


Figure 6: The description of snow stratigraphy during the measurement campaign in three different land cover types; sparse forest on mineral soil (SFm), open bogs (OB), and lake ice (LR). Upper: Bar charts characterize detected snow layers, the maximum diameter of a typical snow grain (E) within each snow layer is indicated with colour. White indicates ice layers where individual snow grains were not detected. Middle: snow temperature profiles. Lower: snow density profiles.



593 Figure 7: Typical exponential fits to the calculated autocorrelation lengths of snow depth measured
594 over forests (DFm, top) and wetlands (OB, bottom) on 1Mar 2012.