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Spatial and Temporal Variability of Snow Bulk Density and Seasonal Snow Densification Behavior in Finland

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Abstract

The spatial and temporal variability of snow bulk density and seasonal snow densification behavior in Finland was studied using comprehensive set of snow survey data. Mapping of the monthly snow bulk densities showed small differences, mainly indicating slightly denser snow covers in the open areas compared to the dense forest conditions. Open areas / forest openings had statistically different snow densities compared to forested conditions most often during the melt period. On average, Finnish snow has a bulk density of approximately 200 kgm^{-3}*during the early winter, and bulk density increases to approximately 230 kgm*$^{-3}$ *in March and to more than 280 kgm*$^{-3}$ *in April. The average densification behavior of the Finnish snow cover locates the country on a transition zone between the maritime and taiga snow zones. Early winter snow bulk densities showed decreasing trends at some locations and/or biotypes during recent decades; during the melt period some increasing trends were seen. Trends seen in long time series of the snow densification behavior were mostly small. Some significant increasing trends in snow densification were observed in the long times series from Jokioinen, Konnevesi and Kittilä. Densification behavior among the biotypes did not differ significantly.*

Keywords: snow, snow density, snow zonation, snow surveys

1 Introduction

Snow is an important element in the boreal environment. Snow covers many areas in Finland over half of the year, and 40–50% of the yearly precipitation is snow (*Mustonen*, 1965; *Solantie et al.*, 1996). Snow changes the physical and chemical environment for the plants, and it is among the most important single factors affecting the overwintering of ground vegetation by decreasing the ground frost (e.g. *Repo et al.*, 2005), sheltering the plants from the frost and drought, attenuating the solar radiation, and freeing large fraction of the annual precipitation during the beginning of the growth

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season. (e.g. *Brooks and Williams*, 1999) Also animals may depend on the amount and quality of snow in finding food or shelter, classic examples being reindeer (*Kumpula and Colpaert*, 2007), black grouse (*Lindén*, 1981) and small rodents (*Hansson and Henttonen*, 1985; *Eccard and Ylönen*, 2001).

Seasonal snow cover consists of layers, resulting from successive precipitation events. Mass and energy transfer at snow-air, and also to less extent at soil-snow interface cause temperature and water vapor gradients between and within the snow layers. These lead to metamorphoses, which change snow grain size, form and bonding. Metamorphoses can be divided to equilibrium growth metamorphosis (rounding of grains, increase in grain bonding and snow density), kinetic growth metamorphosis (depth hoar formation, loss of bonding) and wet snow metamorphosis (melt or melt-freeze of snow, increase in snow density and strength). (*Marbouty*, 1980; *Colbeck*, 1982; *Fukuzawa and Akitaya*, 1993; *Brown et al*., 1997; *Fierz and Baunach*, 2000) Snow metamorphoses lead to changes in snow heat and radiation conductivities, which in turn have direct effect on living conditions below the snow. As a generalization, seasonal snow metamorphoses tend to result in increased snow bulk density (*Sturm and Holmgren*, 1998).

Weather conditions determine which types of metamorphoses a certain snow layer experiences during a certain winter. Snow conditions can be classified using the average winter climatic conditions (temperature, wind speed and snow precipitation) as well as observed physical properties of snow, as described by *Sturm et al.* (1995). This scheme has been used in Finnish conditions by *Oksanen* (1999). In 1998, *Sturm and Holmgren* reported on method which gives more information on geophysical and ecological snow conditions among the snow zones found using this scheme; a distinct snow densification behavior was defined for the different snow zones.

The local mass and energy balances of the snow cover, determining the metamorphic development of the snow, and through this, snow densification, are largely determined by local topography and vegetation, especially by the forest cover. E.g. in Scandinavia the terrain has a mosaic-kind of structure of open areas and different forest types, possibly leading to largely varying small scale densification behavior. The effect of forest depends on tree and canopy type and density. In most of the cases, snow depth and snow water equivalent in the forest are reduced compared to the open-land due to interception, evaporation losses of intercepted snow and enhanced wintertime snowmelt below the canopy (e.g. *Vehviläinen*, 1992; *Harding and Pomeroy*, 1996; *Lundberg and Koivusalo,* 2003; *Stähli and Gustafsson*, 2006; *Veatch et al*., 2009). Snow accumulation is normally higher under deciduous trees and less under coniferous species (*Pomeroy and Gray*, 1995). Forest affects also on snow surface energy balance (*Davis et al*., 1997; *Essery et al*., 2008) by changing intensities of incoming short wave radiation (*Pomeroy and Dion*, 1996; *Hardy et al*., 2004) and long wave radiation (*Rowlands et al*., 2002), as well as causing large spatial variability in the incoming radiation.

Differing snow densification behavior may occur among open areas and different forest types. In areas of high snow accumulation, larger snow mass in the open area may lead to more efficient compaction and higher densities in the open area compared to the forest (*Lundberg and Koivusalo*, 2003). Higher wind exposure may also increase the rate of compaction in the large open areas (*McKay and Gray*, 1981). On the other hand, snow unloading from trees can locally result in compaction of the snowpack under the canopy (*Lundberg and Koivusalo*, 2003). In a study by *Vadja et al*. (2006) in subarctic Fennoscandia the snow density was not observed to vary considerably between forested and open area. But in measurements described by *Stähli and Gustafsson* (2006) a much larger difference was found between the open area and forest snow water equivalent than between the open area and forest snow depth in a sub-alpine catchment. This was assumed to be due to the larger snow cover settling outside the forest due to larger over-burden pressure and radiation exposure. During the melt period, different rates of melt in the open and forest may lead to differences in snow densification (*Lundberg and Koivusalo*, 2003).

Snow density has been studied very little in Finland. The snow density profile evolution was studied by *Simojoki and Seppänen* (1963). The studies by *Oksanen* (1999) and *Rasmus* (1999, 2005) collected more thorough information on snow cover structure in Finland. Extensive Finnish snow survey data collected by Finnish Environment Institute is commonly used to estimate snow mass and its evolution on certain area. Direct density observations are rarely used, even though density is a function of snow structure, and densification tells about snow metamorphic changes. Obtaining snow structure data is a time and labor demanding task. It is still important information in several winter ecological applications, e.g. when studying the role of snow in winter time survival of black grouse or small mammals or foraging conditions of reindeer.

In this work I aim to understand the spatial and temporal variability of snow density and densification behavior in Finnish conditions and their long-term changes.

2 *Material and methods*

2.1 *Finnish Environment Institute snow surveys*

Large database from Finnish Environment Institute snow surveys makes it possible to study both temporal and spatial variation of snow bulk density and seasonal snow densification. It is also possible to divide the snow survey data to different terrain types or biotypes. Main purpose of the measurements is to provide estimates of the average areal snow water equivalent (snow mass per area) (*Kuusisto*, 1984; *Reuna*, 1994), but the estimates are based on snow depth and density observation on the surveys.

Finnish Environment Institute operates approximately 150 snow surveys around the country; the maximum amount of surveys during the years has been around 180. First snow surveys date back to year 1935. Most of the surveys are 4 km long with 80 snow depth and 8–10 snow density measurements. Snow depth is measured every 50m using a snow probe. Snow density is measured as a bulk density by Korhonen-Relander model snow scale. First a snow sample is taken pushing a cylindrical tube (cross-sectional area $0{,}01\text{m}^{-2}$) vertically through the whole snow cover and then weighing this with a special scale. (If snow depth exceeds 50cm, taking the sample may require weighing more than one sample, or alternatively noting the total depth and compressing the snow in the sampler.) The surveys situated on so called small research basins are 2 km long, on which 50 snow depth measurements and eight snow bulk density measurements are conducted ("small surveys"). On the small surveys the measurement points are fixed; on the other ones only the location of the survey is fixed, but each snow survey is designed to include the typical terrain and biotypes of the region. At least one snow density measurement is taken in each of the terrain types. The aspect, local topography, terrain type, tree species and forest density class are observed visually for each measurement point. Topography is characterized as a hilltop, a hill slope, a depression or a flat. The slope of the terrain, as well as the forest density are reported on a scale from 0 to 5. The two main terrain types are open and forest, open being divided into large open areas, forest clearings (the diameter of the opening recorded) and bogs. Forests are divided into pine, spruce, deciduous and mixed. Observer makes notes also on special snow situations and ice on the ground. (*Kuusisto*, 1984; *Perälä and Reuna*, 1990)

Until year 1968 the snow surveys were made on 16th day of the winter months. Since that, observations were tried and made also on 1st day of the month until year 1996, after which only the observations on 16th day of the month were continued. On the small surveys the observations are made also on 1st day of the month during the melt period.

For each snow survey the data is pre-processed at Finnish Environment Institute. Snow bulk densities of different biotypes are calculated as a simple average of the density observations from a biotype. Using this and snow depth observations, snow water equivalents are estimated, and simple averages of depth and snow water equivalents calculated for each biotype. For small surveys only average values for the area are available. The time series from the snow surveys are not totally homogenous because of the some changes in observation locations, observers and observation environment (e.g. forest growth and logging). During 1970s and 1980s also additional observations (from Finnish Meteorological Institute, water and environmental districts and hydroelectric companies) were taken into account. In northern Finland the coverage of the surveys is poorer than in other parts of the country, and in open fell areas only few surveys are conducted.

The snow survey data was used in following ways in this study:

1. Spatial variation of snow density was studied collecting together all available Finnish Environment Institute snow survey data from winters 1995/1996 – 2000/2001. Snow depth, water equivalent and bulk density were available monthly for different biotypes separately (some of the data may lack for various reasons). This data has been used to map the snow bulk density at different biotypes and during different winter months (from December to April), as well as to map the snow densification behavior at different biotypes for the whole country.

2. Temporal variation of snow density and densification was studied using five long-term time series, chosen from Finnish Environment Institute snow surveys: from Tammela (Liesjärvi), Jokioinen, Jyväskylä, Konnevesi (Särkisalo)

and Kittilä (Pokka) (See Fig. 1). From each location, snow depth, snow water equivalent and snow bulk density were available monthly for different biotypes separately. Data may lack from certain locations and from some of the biotypes because of the local conditions; also some observations are missing because of the winter conditions or possible changes in the observation system. From Tammela data from 27 winters was available (years 1960–1986), 30 from Jokioinen (from total 62 years time-span between years 1946–2008, gaps between years 1968–1991 and between years 1994–2002), 22 from Jyväskylä (years 1966–1990), 35 from Konnevesi (years 1960–1994) and 39 from Kittilä (from total 49 years time-span between years 1960–2008, a gap between years 1994–2002). The average monthly snow densities (from December to April) at different biotypes were studied, with a special emphasis on decadal changes in snow density at different biotypes and during different winter months, and on the decadal changes in the snow densification behavior at different biotypes, using the characteristic bulk density versus time curves described below.

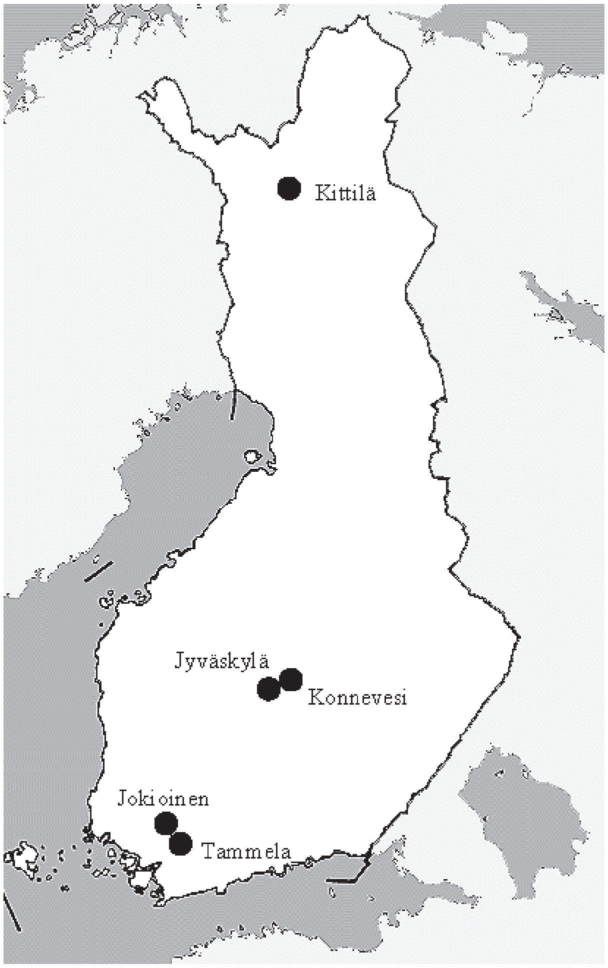

Fig. 1. Location of the snow surveys with the long-term observations on snow depth and density used in this study.

2.2 *Characteristic bulk density versus time curves*

To study the densification of seasonal snow, a simple method originally used in development of the global snow zonation scheme by *Sturm and Holmgren* (1998) was applied.

In work by *Sturm and Holmgren* (1998) it was assumed, that distinctive snow bulk densification behavior can be seen among different climatic conditions. Characteristic bulk density versus time curves were determined for three snow zones using the snow pit observations from two locations in Northern America for each snow class, and also data from snow surveys operated by the US Department of Agriculture National Resources Conservation Service. Three years of snow pit observations and 11 winters of snow survey data was used. The data represent the average snow conditions of each area.

Each data was fitted with a line:

$$\overline{\rho} = mt + b \tag{1}$$

Where t is time in days measured from 1 January, m is the slope of the curve and b is the intercept at t = -65 d (10^{th} of October). Density ρ is measured in kgm^{-3}. The intercept value has been defined as a bulk density value at the start of the winter in Northern American conditions. Finally the average slope and intercept values were calculated for each snow zonation class. In this work, this method was used to estimate the slope values of the bulk density versus time curves from the snow survey data.

2.3 *Statistical analysis*

Statistical analysis of the snow survey data was done using the Systat 13 software. Trends and statistical significance of the observed trends were examined using the Mann–Kendall test. The unpaired two-sample t-test was used to determine the differences between the observations from different biotypes or decades. T-test was done as two-tailed and assuming equal variance for the two samples.

3 *Results*

3.1 *Spatial variation of snow density and densification*

3.1.1 *Mapping of snow bulk density at different biotypes and during different winter months*

Some examples of the spatial distribution observations of monthly snow bulk densities are gathered in Figure series 2. Small differences, mainly indicating slightly denser snow covers in the open areas compared to dense forest conditions, are seen between the snow bulk density values observed in the open areas and below spruce canopies from April 1996 (Fig. 2a). Snow densification during a winter is demonstrated when comparing the average snow bulk density values from January and April 1995/1996 (Fig. 2b).

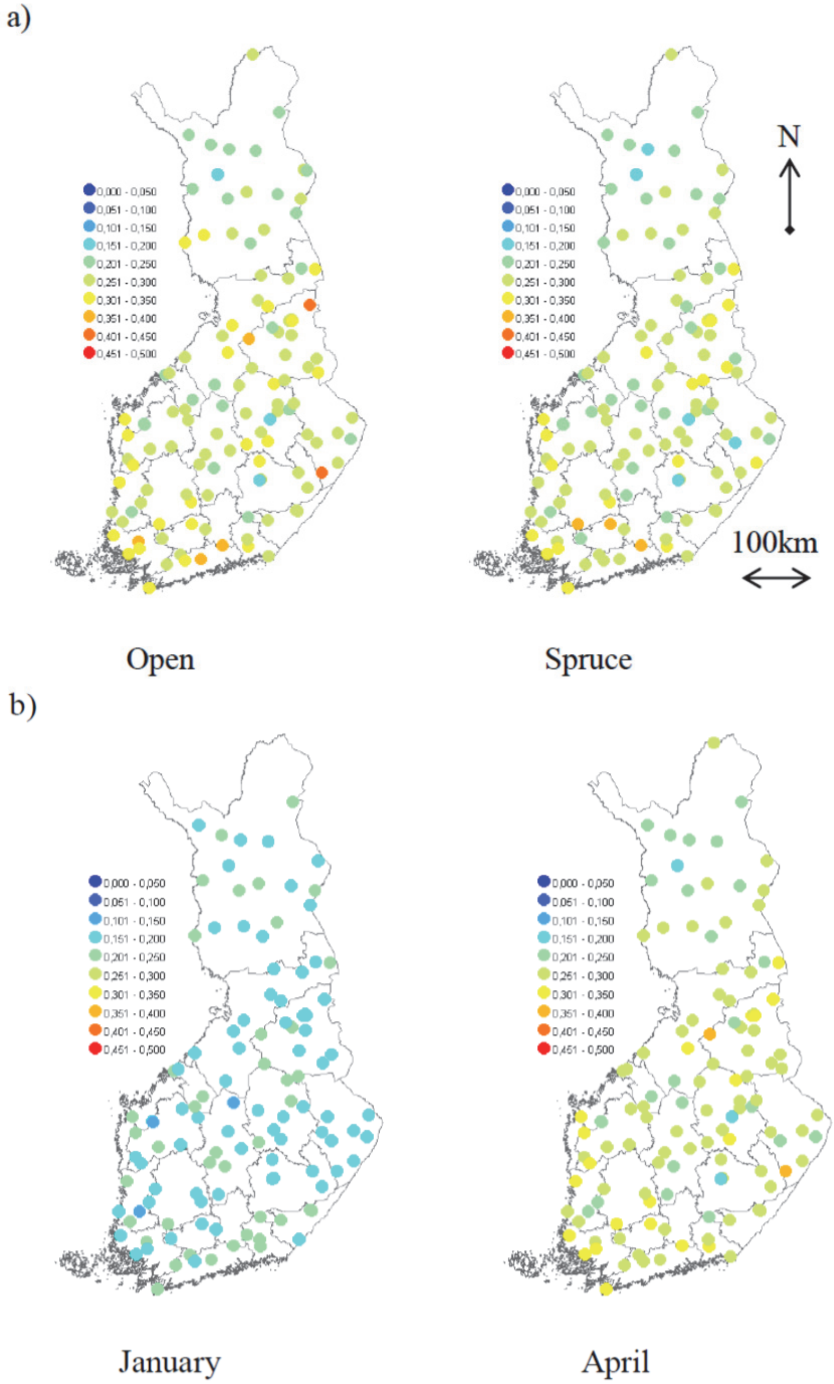

Fig. 2 (a–b). Spatial distribution of snow bulk densities (gm^{-3}) in April 1996 in the open areas and below the spruce canopies (a); spatial distribution of average snow bulk densities (gm^{-3}) in January and April 1995/1996 (b). (Data from Finnish Environment Institute snow surveys.)

Average bulk snow densities are gathered in Table 1 for the whole country for each winter month separately. Data for the whole six winter period was used in the calculations (standard deviation is shown in parentheses). Even if the areal variation within the country is lost in this data, it reveals the overall density evolution of the Finnish snow cover, and the role of the biotype.

Table 1. Average monthly snow bulk densities (kgm^{-3}), using open area, spruce and pine forest observations from the whole country, from six consecutive winters. Standard deviation in the parentheses. (Data from Finnish Environment Institute snow surveys.)

	Jan	*Feb*	*Mar*	*Apr*
Mean	196 (5.3)	204 (4.7)	233 (5.0)	285 (6.3)
Open	199 (5.9)	207 (5.0)	236 (5.4)	290 (6.8)
Spruce	197 (5.7)	204 (5.1)	231 (5.2)	284 (6.8)
Pine	195 (5.5)	205 (5.0)	235 (5.4)	285 (6.6)

3.1.2 Mapping of snow densification behavior at different biotypes and snow zonation

Spatial variation of the slope values of the characteristic bulk density versus time curves is shown in the Figure series 3 (a-b) based on the snow survey observations. Slope values were calculated (see Section 2.2.) using all available snow survey data between winters 1996/1997 and 2000/2001, for open areas (a) and spruce forests (b). Tundra, taiga, maritime and ephemeral and the transition classes taiga/tundra and maritime/taiga refer to the densification classes in the snow zonation by Sturm et al. (1995) and Sturm and Holmgren (1998). In these it was assumed that e.g. ephemeral snow results from distinctive climatic conditions, and this leads to snow densification behavior typical to these conditions. Ephemeral snow has a slope value of bulk density versus time curve of more than 2.04 kgm^{-3}d^{-1}, maritime between 1.03–2.04 kgm^{-3}d^{-1}, taiga between 0.53–0.72 kgm^{-3}d^{-1}, and tundra between 0.10–0.43 kgm^{-3}d^{-1} (see Section 2.2. for more details). Transition classes between the listed ones have slope values that fall between the ranges given here. Maps show only slight differences in densification behavior between the biotypes.

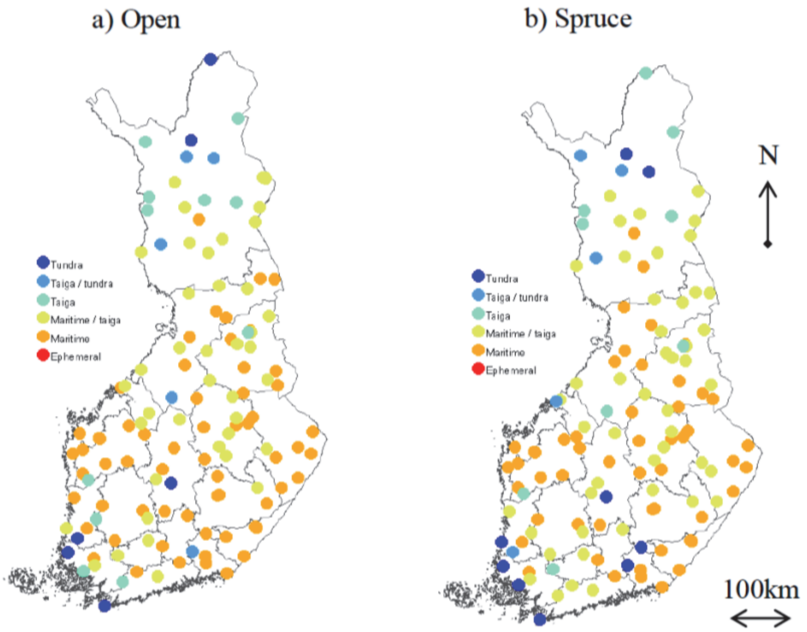

Fig. 3 (a–b). Spatial variation of the mean slope values of the snow bulk density versus time curves (data from winters 1996/1997–2000/2001) in the open areas (a) and below the spruce canopies (b). Tundra (dark blue), taiga (light blue), maritime (orange) and ephemeral (red) refer to the densification classes in snow zonation by *Sturm et al*. (1995) and *Sturm and Holmgren* (1998) (Data from Finnish Environment Institute snow surveys.)

The five year averages of the slopes of the density versus time curves (Table 2) give an idea of the average snow densification behavior in Finland. Also minimum and maximum values, standard deviations and coefficients of variations are shown, and snow survey mean values, pine and spruce forest data and open area data are handled separately. Slightly more efficient snow densification is seen in the open areas when compared to forested areas – slope values were a bit lower below the spruce than below the pine canopies. Applying the scheme introduced by *Sturm and Holmgren* (1998), the average densification behavior of the Finnish snow cover locates the country on a transition zone between the maritime and taiga snow zones.

Table 2. Average slope of the snow bulk density versus time curves (kgm^{-3}d^{-1}), using open area, spruce and pine forest observations from the whole country, for six consecutive winters. Also standard deviations and coefficients of variations within the country are shown. (Data from Finnish Environment Institute snow surveys.)

	Mean	*Open*	*Spruce*	*Pine*
Average	0.99	1.01	0.94	0.98
St. dev	0.66	0.70	0.74	0.71
Coef. var	0.67	0.69	0.79	0.72

3.2 Temporal variation of snow density and densification at selected locations

Temporal variation of snow density and densification was studied using five long-term time series, chosen from Finnish Environment Institute snow surveys: from Tammela, Jokioinen, Jyväskylä, Konnevesi and Kittilä (Fig. 1).

3.2.1 Monthly average snow densities at different biotypes and during different winter months

In table 3 (a-e) the average snow bulk densities for each biotype and each winter month for the study locations (standard deviation and coefficient of variation show in brackets) are shown, for the whole study period. Number of years used in calculations, n, is shown in brackets for each case. The data may be missing for some biotypes and some decades. Most of the differences in snow bulk density among the biotypes are seen in early winter and during the melt period. During the melt period open areas had the densest snow covers at each location.

Table 3(a-e). Average snow bulk densities (kgm^{-3}) for each biotype and each winter month for Tammela, Jokioinen, Jyväskylä, Konnevesi and Kittilä (standard deviation and coefficient of variation shown in brackets), for the whole study period. Number of years used in calculations, n, is shown in brackets for each case. (Data from Finnish Environment Institute snow surveys.)

a) Tammela

	Open	*Forest opening*	*Pine*	*Spruce*	*Birch*	*Mixed*	*Bog*
December (15)	-	121 (38; 0.31)	146 (50;0.34)	171 (55; 0.32)	143 (37; 025)	162 (59; 0.37)	-
January (22)	-	175 (62;0.36)	180 (92;0.51)	192 (97;0.50)	231 (114;0.50)	191 (121;0.63)	-
February (26)	-	190 (54;0.28)	186 (56;0.30)	192 (66;0.35)	156 (43;0.27)	178 (50;0.28)	-
March (26)	-	228 (53;0.23)	235 (65;0.28)	232 (80;0.35)	218 (64;0.29)	216 (56;0.26)	-
April (14)	-	358 (78;0.22)	310 (67;0.22)	309 (56;0.18)	322 (99;0.31)	305 (60;0.20)	-

b) Jokioinen

	Open	*Forest opening*	*Pine*	*Spruce*	*Birch*	*Mixed*	*Bog*
December (14)	200 (78;0.39)	183 (66;0.36)	187 (78;0.41)	161 (59;0.37)	169 (47;0.28)	-	-
January (24)	187 (62;0.33)	192 (71;0.37)	178 (58;0.33)	-	194 (75;0.39)	-	168 (73;0.43)
February (30)	226 (54;0.24)	217 (37;0.17)	211 (47;0.22)	199 (50;0.25)	215 (35;0.16)	-	-
March (30)	245 (55;0.22)	237 (54;0.23)	246 (57;0.23)	224 (60;0.27)	238 (47;0.20)	-	-
April (13)	311 (65;0.21)	305 (25;0.083)	-	292 (46;0.16)	304 (35;0.11)	-	-

c) Jyväskylä

	Open	*Forest opening*	*Pine*	*Spruce*	*Birch*	*Mixed*	*Bog*
December (18)	166 (34;0.21)	163 (35;0.22)	180 (50;0.28)	176 (56;0.32)	165 (46;0.28)	176 (51;0.29)	172 (43;0.25)
January (21)	199 (33;0.16)	207 (31;0.15)	201 (42;0.21)	196 (48;0.24)	205 (31;0.15)	200 (46;0.23)	204 (39;0.19)
February (22)	212 (30;0.14)	209 (33;0.16)	216 (34;0.16)	211 (51;0.24)	211 (34;0.16)	223 (50;0.22)	212 (30;0.14)
March (22)	245 (38;0.16)	236 (30;0.13)	251 (33;0.13)	253 (34;0.13)	243 (33;0.14)	244 (34;0.14)	241 (39;0.16)
April (20)	328 (29;0.09)	324 (26;0.08)	312 (40;0.13)	298 (46;0.15)	305 (55;0.18)	309 (31;0.10)	296 (47;0.16)

d) Konnevesi

	Open	*Forest opening*	*Pine*	*Spruce*	*Birch*	*Mixed*	*Bog*
December (31)	177 (58;0.33)	179 (74; 0.41)	181 (50;0.28)	190 (57;0.30)	168 (56;0.33)	176 (63;0.36)	181 (63;0.35)
January (32)	190 (34;0.18)	198 (37;0.19)	190 (45;0.24)	189 (45;0.24)	183 (33;0.18)	202 (49;0.24)	193 (41;0.21)
February (34)	195 (30;0.16)	197 (34;0.17)	185 (32;0.18)	198 (33;0.17)	196 (37;0.19)	202 (35;0.17)	206 (29;0.14)
March (32)	231 (36;0.15)	236 (48;0.20)	224 (44;0.20)	234 (46;0.20)	232 (43;0.19)	228 (36;0.16)	226 (44;0.19)
April (31)	314 (52;0.17)	317 (52;0.16)	299 (43;0.14)	296 (40;0.14)	302 (33;0.11)	306 (49;0.16)	301 (40;0.13)

e) Kittilä

	Open	*Forest opening*	*Pine*	*Spruce*	*Birch*	*Mixed*	*Bog*
December (31)	176 (21;0.12)	177 (16;0.093)	185 (21;0.11)	172 (24;0.14)	184 (26;0.14)	-	177 (28;0.16)
January (36)	189 (22;0.12)	194 (18;0.09)	195 (24;0.12)	180 (26;0.15)	190 (27;0.14)	-	195 (30;0.15)
February (38)	204 (24;0.12)	200 (22;0.11)	208 (26;0.12)	195 (25;0.13)	203 (24;0.12)	-	205 (24;0.12)
March (37)	222 (25;0.11)	208 (23;0.11)	227 (30;0.13)	214 (31;0.14)	222 (30;0.13)	-	223 (31;0.14)
April (37)	267 (37;0.14)	216 (29;0.13)	256 (37;0.14)	247 (40;0.16)	257 (45;0.18)	-	266 (52;0.19)

Also according the T-test, open areas / forest openings had statistically different snow densities most often during the melt period. In Kittilä, the snow density at all of the biotypes differed from the open area density during April (p-values from 0.003 to 0.048). In Jokioinen, only statistically significant difference was the denser snow in the open areas compared to the spruce forest snow during February (p=0.048). In Jyväskylä in April, snow was statistically significantly denser in the open area than in the spruce forest or in the bog environment (p=0.08 and 0.05). In Tammela during December, pine, spruce and mixed forests had statistically significantly denser snow cover than the forest openings (0.06, 0.003, 0.03). In Konnevesi there was no statistically significant difference between the open area and other biotype snow densities during any of the winter months.

3.2.2 Long-term changes in monthly snow densities at different biotypes and during different winter months

Long time series of snow bulk densities were analyzed for each winter month and location separately and linear trends were looked for in the data. Statistically significant trends are listed in Table 4.

In Jyväskylä and in Konnevesi, both located in mid-Finland, early winter snow bulk density showed decreasing trends at some biotypes. During mid-winter and/or during the melt period a general increasing trend was seen. Snow bulk density in Kittilä, northern Finland, showed weak decreasing trends both during the early winter and also in mid-winter. April was the only month where an increase in snow bulk density was seen. Tammela showed some contradictory trends – increase in snow bulk density during the early winter and decrease during April. Tammela is located in the southern part of the country, and during some winters melt happens here earlier than at the other study sites. This has an effect on April snow densities, and makes interpretation of this result difficult.

Table 4. Locations, months and biotypes with statistically significant trends in the monthly mean snow densities. Slope estimate (kgm^{-3}yr^{-1}), n and p-values are listed. From Tammela not enough open area / birch forest observations were available for a reliable trend analysis. (Data from Finnish Environment Institute snow surveys.)

	Slope estimate	*n*	*p*
Tammela			
February, forest opening	2.74	18	0.027
April, pine	-3.23	14	0.042
April, spruce	-3.47	14	0.011
Jyväskylä			
December, mixed forest	-2.96	18	0.02
January, forest opening	4.22	17	0.000
January, bog	2.00	21	0.05
February, open	3.00	19	0.002
February, forest opening	2.42	18	0.003
February, spruce	3.82	22	0.009
February, birch	3.16	17	0.000
February, mixed	2.01	20	0.037
February, bog	2.35	21	0.003
Konnevesi			
December, bog	-3.35	20	0.039
February, open	1.07	30	0.044
February, forest opening	1.74	25	0.000
February, spruce	1.33	34	0.021
February, birch	1.63	26	0.047
February, mixed	1.62	21	0.002
February, bog	1.66	17	0.002
March, pine	1.53	28	0.013
March, spruce	2.18	31	0.012
March, birch	1.33	26	0.034
April, forest opening	1.65	22	0.037
April, pine	1.57	25	0.034
April, birch	1.19	22	0.014
April, bog	1.40	18	0.000
Kittilä			
November, forest opening	-5.50	8	0.000
December, open	-0.54	15	0.036
December, pine	-0.64	32	0.005
December, birch	-0.67	29	0.010
January, birch	-0.44	37	0.033
March, open	-0.48	10	0.000
April, open	2.02	12	0.000

A long gap in the time series from Jokioinen complicated the trend analysis at this location. For this reason, only monthly snow densities and densification between a sample from 1946–1968 and a sample from 1991–2008 were compared. According the t-test, no statistically significant difference was found, even though snow cover was denser during the melt period in the latter sample.

3.2.3 Long-term changes in the snow densification behavior

Trends seen in the densification coefficients in Jyväskylä and Tammela were small and statistically insignificant at all of the biotypes. In Kittilä very small but significant increase was seen in the open area snow densification coefficient during the observation years (slope estimate 0.026 $kgm^{-3}d^{-1}yr^{-1}$, n=20, p=0.018). In Konnevesi, small but significant increase was seen in the snow densification coefficients observed in spruce forest (0.023 $kgm^{-3}d^{-1}yr^{-1}$, 35, 0.038), mixed forest (0.047 $kgm^{-3}d^{-1}yr^{-1}$, 25, 0.003) and in the bog environment (0.027 $kgm^{-3}d^{-1}yr^{-1}$, 22, 0.048). In Jokioinen, birch forest snow showed small but significant decrease in densification coefficient (-0.018 $kgm^{-3}d^{-1}yr^{-1}$, 19, 0.008). The slope values of the density versus time curves through the decades are showed in the Figure series 4 for Jokioinen, Konnevesi and Kittilä with significant trends included. Forest opening, mixed forest and bog data are omitted from the figures.

3.2.4 Snow densification behavior at different biotypes

According the t-test, densification coefficients from other biotypes did not differ significantly from those observed in the open areas at any of the sites. A score method was developed to evaluate which of the biotypes most often had relatively dense snow covers compared to others, and how did this situation change during the different winter months. In table 5 (a-e) the biotypes of each location are sorted according the relative order of their snow bulk density during different winters, for each winter month separately, taking all winters in the time series into account. Each biotype was given a score, summing the times it was last, meaning it had least dense snow cover, in the sorting (0 points), second last (1 point), third last (2 points) etc. The values in parentheses give the score value for each biotype obtained using this method. The results based only on less than five observations are marked with grey shading. High score value means that the snow density of the biotype has been relatively high during several of the winters.

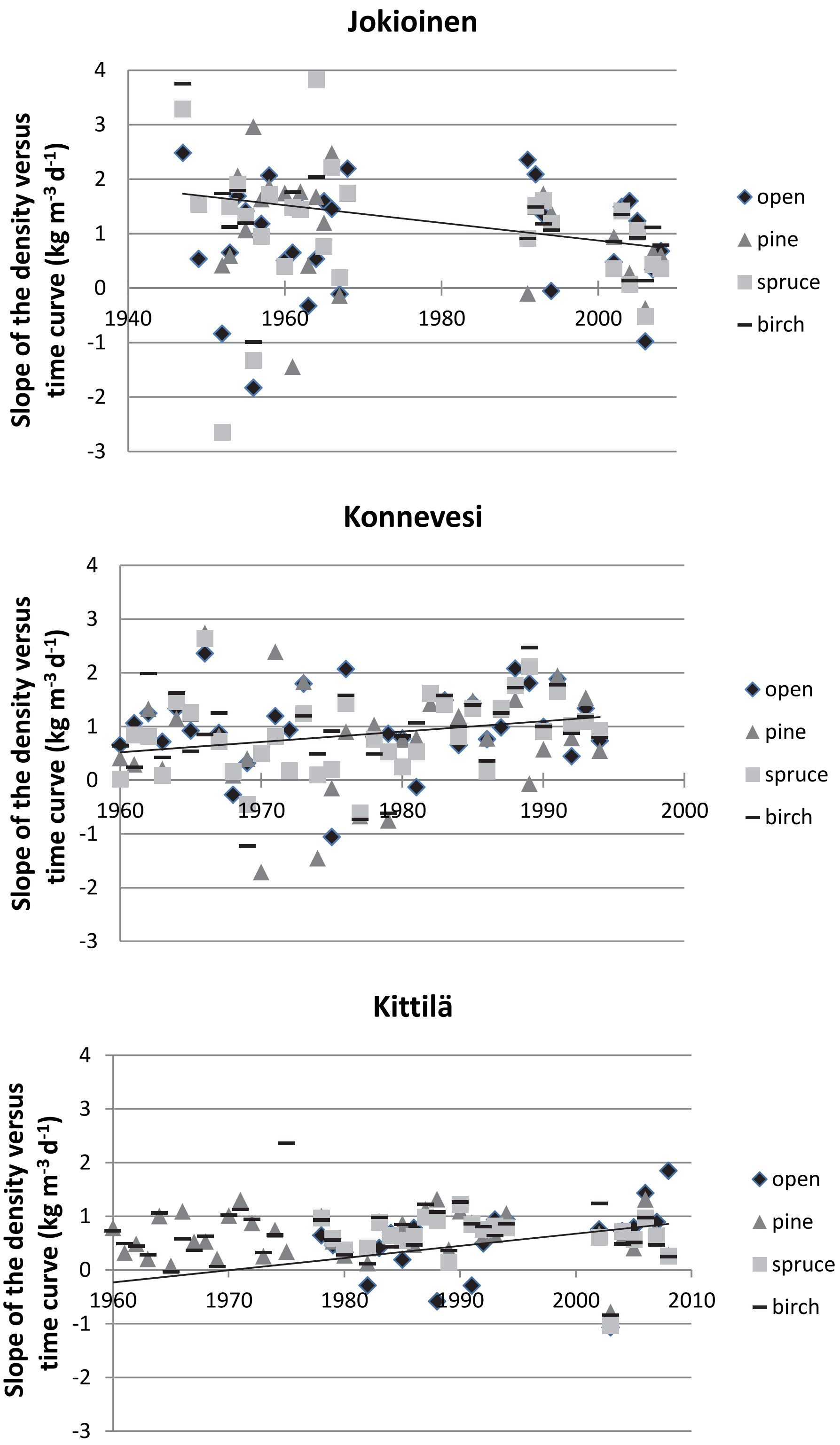

Fig. 4. Long time series of the slope value of the snow bulk density versus time curves in Jokionen, Konnevesi and Kittilä. Forest opening, mixed forest and bog data omitted. Trend lines included for birch forest in Jokioinen (slope estimate -0.018 kgm^{-3}d^{-1}yr^{-1}, p=0.008), spruce forest in Konnevesi (0.023 kgm^{-3}d^{-1}yr^{-1}, 0.038) and open area in Kittilä (0.026 kgm^{-3}d^{-1}yr^{-1}, 0.018). (Data from Finnish Environment Institute snow surveys.)

Table 5 (a-e). Relative order of biotypes in Tammela, Jokionen, Jyväskylä, Konnevesi and Kittilä, according the snow bulk density during different winters, for each winter month separately. The values in parentheses give the score value for each biotype, high score indicating the densest snow covers found often on this biotype. The results based only on less than five observations are marked with grey shading. (Data from Finnish Environment Institute snow surveys.)

a) Tammela

	Dec	*Jan*	*Feb*	*Mar*	*Apr*
1st	Spruce (21)	Spruce (38)	Spruce (41)	Pine (45)	Forest opening (30)
2nd	Mixed (21)	Pine (37)	Pine (39)	Forest opening (39)	Spruce (22)
3rd	Pine (16)	Mixed (35)	Forest opening (31)	Spruce (39)	Pine (21)
4th	Forest opening (8)	Forest opening (31)	Mixed (30)	Mixed (32)	Mixed (21)
5th	Birch (5)	Birch (5)	Birch (12)	Birch (14)	Birch (8)
6th	Open (4)		Open (6)	Open (5)	Open (4)

b) Jokioinen

	Dec	*Jan*	*Feb*	*Mar*	*Apr*
1st	Open (40)	Open (46)	Open (94)	Open (88)	Open (27)
2nd	Pine (29)	Pine (33)	Pine (61)	Pine (60)	Spruce (18)
3rd	Birch (24)	Birch (30)	Forest opening (53)	Forest opening (54)	Birch (15)
4th	Forest opening (15)	Forest opening (29)	Birch (50)	Birch (37)	Forest opening (8)
5th	Spruce (12)	Bog (2)	Spruce (33)	Spruce (27)	
6th			Bog (1)		

c) Jyväskylä

	Dec	*Jan*	*Feb*	*Mar*	*Apr*
1st	Bog (53)	Bog (74)	Bog (64)	Spruce (70)	Forest opening (60)
2nd	Pine (48)	Forest opening (60)	Open (62)	Bog (70)	Open (56)
3rd	Spruce (44)	Birch (58)	Mixed (61)	Pine (64)	Birch (45)
4th	Birch (44)	Spruce (49)	Pine (52)	Mixed (55)	Spruce (43)
5th	Mixed (44)	Mixed (49)	Birch (48)	Forest opening (40)	Mixed (43)
6th	Forest opening (42)	Pine (39)	Forest opening (47)	Open (37)	Bog (40)
7th	Open (37)	Open (36)	Spruce (41)	Birch (35)	Pine (33)

d) Konnevesi

	Dec	*Jan*	*Feb*	*Mar*	*Apr*
1st	Open (85)	Open (79)	Spruce (82)	Spruce (76)	Forest opening (76)
2nd	Spruce (78)	Spruce (71)	Open (76)	Open (75)	Open (69)
3rd	Pine (60)	Forest opening (68)	Mixed (67)	Forest opening (70)	Birch (55)
4th	Forest opening (51)	Pine (67)	Forest opening (63)	Birch (66)	Spruce (55)
5th	Bog (48)	Mixed (62)	Birch (63)	Pine (64)	Pine (53)
6th	Birch (46)	Bog (52)	Pine (50)	Mixed (45)	Bog (49)
7th	Mixed (38)	Birch (50)	Bog (41)	Bog (33)	Mixed (37)

e) Kittilä

	Dec	*Jan*	*Feb*	*Mar*	*Apr*
1st	Pine (83)	Bog (83)	Pine (90)	Pine (81)	Pine (77)
2nd	Birch (68)	Pine (81)	Bog (74)	Birch (62)	Bog (67)
3rd	Bog (58)	Birch (67)	Birch (60)	Bog (54)	Birch (66)
4th	Spruce (32)	Open (32)	Spruce (34)	Spruce (51)	Spruce (37)
5th	Open (28)	Forest opening (25)	Open (27)	Forest opening (22)	Open (34)
6th	Forest opening (21)	Spruce (27)	Forest opening (24)	Open (19)	Forest opening (19)

In Tammela the densest snow cover was bit surprisingly often found below the spruce canopies. Towards spring, forest opening had the highest ranking. No clear differences could be seen among the other biotypes. Small amount of data at birch/open locations also has an effect. In Jokioinen the spruce locations had the most porous (least dense) snow cover. The highest density values were observed at open locations and below pine canopies. Rather even densities were observed among the biotypes in Jyväskylä. The snow cover was often densest at bog locations; and during the spring time, at open areas. During early winter the most porous snow was found at open locations. In Konnevesi the densest snow cover was seen often at open or spruce locations. During spring time the forest opening ranked highest. Different forest types had the more porous snow covers. The amount of data from different biotypes may affect the results in Kittilä. Open areas and forest openings ranked often low, but their amount of data was rather small. Spruce forests had also porous snow cover. The biotypes with the densest snow cover were pine and bog.

The score method was also used to evaluate which of the biotypes most often had relatively high snow densification rates compared to others. In table 6 the biotypes are sorted according the relative order of the slopes of their bulk density versus time curves for each year in the time series. Each biotype was given a score, summing the times it was last, meaning it had least densifying snow cover, in the sorting (0 points), second last (1 point), third last (2 points) etc. The values in parentheses in table 6 give the score value for each biotype obtained using this method. The results based only on less than five observations are marked with grey shading. High score value means that the snow densification of the biotype has been relatively effective during several of the winters.

In Jyväskylä the open areas were clearly densifying more efficiently. In Kittilä the situation between the areas was quite even, one reason being the dominating role of pine forest and bogs. Few data was available from forest openings. In Tammela only few biotypes had good data. Forest opening densified more than forests. Same can be said about Konnevesi, where most of the biotypes had quite even situation, and mixed forest and bogs had clearly less data compared to other biotypes. In Jokioinen, few data was available from birch forest and forest openings. Like in Kittilä, situation among the biotypes was quite even, pine and open areas sharing the top two places.

Table 6. Relative order of biotypes in Tammela, Jokionen, Jyväskylä, Konnevesi and Kittilä, according the slope of the snow bulk density versus time curve. The values in parentheses give the score value for each biotype, high score indicating the most efficient snow densification found often on this biotype. The results based only on less than five observations are marked with grey shading. (Data from Finnish Environment Institute snow surveys.)

	Tammela	*Jokioinen*	*Jyväskylä*	*Konnevesi*	*Kittilä*
1st	Forest opening (38)	Pine (69)	Forest opening (68)	Forest opening (62)	Pine (59)
2nd	Pine (32)	Open (60)	Open (65)	Birch (60)	Bog (59)
3rd	Mixed (29)	Spruce (59)	Spruce (55)	Pine (51)	Open (56)
4th	Spruce (24)	Birch (55)	Mixed (54)	Open (49)	Spruce (55)
5th		Forest opening (42)	Pine (51)	Spruce (47)	Birch (50)
6th			Bog (48)	Mixed (47)	Forest opening (40)
7th			Birch (47)	Bog (40)	

4 *Discussion and conclusions*

Snow density and seasonal snow densification behavior was studied using a comprehensive set of snow survey data. Data was used to map the spatial variability in snow bulk density and seasonal snow densification, and also to study the long term temporal changes in monthly snow bulk densities and seasonal snow densification.

Monthly snow bulk densities showed moderate variation between the winters and within the country. Spring melt started earlier in the south, so latitude had an effect on the spring time density values. Biotype (open area, spruce or pine forest) had only a small, but variable effect on local snow density. During the spring time the open areas had most often the densest snow cover, like assumed. Mapping of spatial variability of the snow densification according to snow survey data also showed slight differences in densification behavior among the biotypes, but more clear temporal variation among the study winters. Areal behavior of snow densification was rather inconsistent, both during single winters and also when using five year average conditions.

Only weak trends could be detected in the long time series of snow bulk density. When a trend was present, it most often showed either slight decrease in early winter density or slight increase in spring density. Trends seen in long time series of the snow densification behavior were mostly small and statistically insignificant. Still some significant, mostly increasing trends in snow densification were observed in the long times series from Jokioinen, Konnevesi and Kittilä. Densification behavior among the biotypes did not differ significantly according the t-test.

Slow alternation between more maritime/continental densification behaviors was seen during the decades, and often the winter weather during a single winter created rather uniform snow density evolution to the whole country. At many locations the 70s and 90s showed the highest snow densification coefficient values. This is in line with observed decadal-scale variability in North Atlantic Oscillation (NAO); phase of NAO being linked to the winter time precipitation and temperature conditions in northern Europe. Several positive NAO index winters were experienced during the 70s and 90s, and e.g. mass balances of many the maritime Scandinavian glaciers were positive during the 90s (*Hurrel and Van Loon*, 1997; *Nesje et al.*, 2000).

Standard deviation of the slope values of the snow bulk density versus time curves among the different biotypes was decreasing at most of the locations. It may be that the areal snow densification conditions are more uniform nowadays than several decades ago, or more probably there has been such a development in the snow survey observation and/or data analysis procedure, which leads to this kind of result.

Interpretation of the results of this study is complicated by the uncertainties and sources of error included in the observations and analysis of the snow bulk density. Generally, conditions on a snow survey are not homogenous, and they also change in time e.g. due to tree growth in the forest or changes in practices in agriculture or forestry (plowing of fields, draining of bogs). Data quality may also vary. E.g. in Jyväskylä the snow survey was observed by army servicemen (during years 1967–1971), so that almost every measurement was done by a different person or group of persons. This has to have direct and indirect effects on data quality through inexperience in measurement technique and uncertainty in measurement timing. In some time series the data was missing for some biotypes and there were long gaps in some of the time series. Sometimes the missing data from some biotypes of the snow survey may be replaced by the mean value of the location. In this kind of conditions selection of a biotype used in the further analysis plays a big role.

Highly variable local snow conditions, originating e.g. from varying local topography or from large year-to-year variation in local winter weather has an effect. Forest ground vegetation patterns and ice on the ground may complicate the density measurements and data interpretation. Timing and length of the snow season and melt period also differs in different parts of the country. Different snow-vegetation interactions in different areas may affect the conclusions: e.g. in subarctic conditions snow drifting has been observed to lead to thinner snow covers in the open area compared to the forest, even though situation is reversed in most of the country (*Vajda et al.*, 2006). The effect of tree or canopy density is not considered in this study. The observers of the snow surveys give also their estimate on the forest density at the snow measurement points. This information may be useful if the effect of the forest cover on the snow density and densification behavior will be studied further.

Applying the scheme introduced by *Sturm and Holmgren* (1998), the average densification behavior of the Finnish snow cover locates the country on a transition zone between the maritime and taiga snow zones. The trend analysis of snow densification used in this study stems from the snow zonation formulation by *Sturm et al.* (1995) and *Sturm and Holmgren* (1998) and has several details that originate from Northern America. The intercept value (date 27.10.) of the characteristic snow bulk density versus time curves has no real meaning in Finnish conditions. From linguistic point of view, the strict use of climatic indicators can result in confusing classification in snow zonation scheme by *Sturm et al.* (1995). For example tundra snow can develop in a prairie environment if the climate falls within the tundra snow class. Also the terminology of the zonation is somewhat problematic in Finland. The maritime snow zone is situated relatively far away from the Baltic Sea, and for this reason also use of a term mild snow zone is suggested. Theoretical snow densification behavior, typical to certain snow zone, is not necessarily a very reliable method to estimate the actual snow properties of a single site in Finland. *Sturm and Holmgren* (1998) report of variation as large as ± 62 $\mathrm{kgm^{-3}}$ in snow bulk density at certain snow zone when estimating snow densities according this method.

The global mean temperature is predicted to increase by 1.4 – 6.4 ^{o}C by the end of the year 2100. The warming is predicted to be especially pronounced during winter in North-Eastern Europe. Precipitation, windiness and cloudiness are also expected to increase. Change is predicted to lead in decrease in amount of snow and length of the snow season, and changes in snow pack structure (*Venäläinen et al.*, 2001; *Räisänen et al.*, 2003; *IPCC*, 2007; *Kellomäki et al.*, 2010). Expected changes in winter climate will lead to different snow densities and densification behavior than we see today. Possible changes mean that there will be changes in e.g. magnitude and timing of the snow density maxima – which have direct effects on timing of snow melt and flood occurrence. They also indicate changes in snow structure and its evolution, leading to changes in living conditions of plants and animals in and below the snow cover. Hence collecting together past and present day snow quality information is of great value anticipating the future changes.

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