Effect of Vegetation on Snow Cover at the Northern Timberline: A Case Study in Finnish Lapland

Andrea Vajda, Ari Venäläinen, Pekka Hänninen and Raimo Sutinen

The presence of permanent snow cover for 200–220 days of the year has a determining role in the energy, hydrological and ecological processes at the climate-driven spruce (*Picea abies*) timberline in Lapland. Disturbances, such as forest fires or forest harvesting change the vegetation pattern and influence the spatial variation of snow cover. This variability in altered snow conditions (in subarctic Fennoscandia) is still poorly understood. We studied the influence of vegetation on the small-scale spatial variation of snow cover and wind climate in the Tuntsa area that was disturbed by a widespread forest fire in 1960. Radar was applied to measure snow thickness over two vegetation types, the spruce-dominant fire refuge and post-fire treeless tundra. Wind modelling was used to estimate the spatial variation of wind speed and direction. Due to the altered surface roughness and the increased wind velocity, snow drifting was more vigorous on the open tundra, resulting in a 30-cm thinner snow cover and almost half the water equivalent compared to the forest values. The changes in local climate after the fire, particularly in snow cover, may have played an important role in the poor recovery of vegetation: a substantial area is still unforested 40 years after the fire.

1 Introduction

Snow is an essential factor in the environment of high latitude regions. The presence of snow for seven to eight months of the year has a determining role in the energy exchange, the hydrological cycle and ecological processes. The snow cover has different properties than the soil surface: due to its high albedo values it modifies the surface radiation budget, changes the aerodynamic characteristics of the surface, but also has a significant influence on the runoff (Harding et al. 2001). The length of the snow period as well as the snow thickness influence the soil thermal conditions, reducing soil frost and increasing the soil temperature. A permanent snow cover lasts 200–220 days of the year in Lapland (Atlas of Finland – Climate 1987). Snowmelt is associated with low evaporation, hence the spring flood following snowmelt typically results in saturation of the root-zone. This is particularly true for fine-grained drift (Sutinen et al. 2002).

An important interaction exists between snow and vegetation. Thick snow cover may have a positive influence on the vegetation by reducing or even preventing soil frost, hence providing protection for plants during winter. On the other hand, there is a feedback mechanism, through which vegetation influences the accumulation and spatial distribution of snow, as well as its physical characteristics (Liston et al. 2002). For example, increased shrub vegetation captures and holds more snow, the length of the snow-covered period increases and melt water production increases late in the melt season. The presence of snow cover influences the fauna as well. For example, snow properties determine the forage accessibility for reindeers: during early winter, when snow is soft, light and thin reindeers can feed on large lichen communities. During late winter, when snow hardness and snow depth increases reindeers select narrow ridges, exposed sites, where snow is more shallow (Pruitt 1979). Exceptionally thick snow pack hampers reindeers' access to food, leading to a reduction in their energy levels (Lee et al. 2000).

A number of studies have been made dealing with the snow conditions of high latitude regions and the interaction between snow and vegetation. Most of the studies have focused on the energy balance of the snow cover, snow dynamics and the behaviour of the soil-snow-atmosphere system in Arctic regions (Gustafsson et al. 2001, Harding et al. 2001, Koivusalo et al. 2001).

The interaction between snow and vegetation in the arctic tundra and the responses of these features to environmental changes are well described in previous studies (Scott et al. 1995, Press et al. 1998, Sturm et al. 2001, Liston et al. 2002). According to these changes in shrub distribution and abundance cause significant changes in snow-depth distribution patterns; this affects the spatial and temporal coupling of the climatically important snow, energy and moisture interaction (Liston et al. 2002). In addition, the positive feedback between snow and shrubs is believed to be able to change land surface processes in the Arctic (Sturm et al. 2001): an increase in shrubs could augment the depth of snow on the ground that consequently results in higher subnivian temperatures, promoting greater winter decomposition and nutrient mineralization. This provides favourable conditions for the growth of shrubs.

Most of the climatological studies carried out in Finnish Lapland have dealt with snow monitoring (Vehviläinen 1992, Koskinen et al. 1999) and the snow energy balance (Koivusalo et al. 2001), but only few studies have focused on the interaction between snow and the subarctic vegetation. The spatial and temporal variation in snow accumulation, snowmelt and snow water equivalent in Finland was studied by Seppänen (1961), Kuusisto (1984), Solantie et al. (1996) and Solantie (2000). According to these, the forests accumulate a thicker snow-cover than the open areas; however the increased amount of forest growing stock enhances the arboreal interception and reduces the snow depth and water equivalent in forested area. According to Seppänen (1961) the water equivalent is higher in open areas than in forests in southern Finland, while this disparity disappears at about 64° N and northwards thereof. The spatial analysis of soil frost confirmed the occurrence of thinner soil frost in regions with more snow, the mean maximum soil frost being with 6 to 9 cm deeper in open fields than in forests (Solantie 2000).

The objective of the current study was to examine how vegetation influences the spatial variation of snow depth on the small scale at the fire-disturbed timberline in the Tuntsa area of Finnish

Lapland. The analysis is based on measurements made in the Tuntsa area, which was impacted by a widespread forest fire in 1960. Despite intensive planting attempts, reforestation has largely failed in the study area. The surface roughness changed due to the forest fire and the removal of the majority of trees from the affected area. This increased wind speed that further led to intensified snow drifting. The spatial variation of wind over the study area was estimated using the WAsP model (Wind Atlas Analysis and Application Program) described by Troen and Peterson (1989). This study aims at providing new information about the feedback mechanisms between the atmosphere and the surface in the sensitive region near the northern timberline, defined as the limit of the closed forest (Hustich 1979). In addition, the study compares two different snow-depth measurement methods: the traditional manual measurement and radar.

2   Methods and Data

2.1 Study Area

The Tuntsa area is located in eastern Finnish Lapland between 67°30´N, 29°30´E and 67°45´N, 30°E (Fig. 1). There is no meteorological station in the study area, but the dominant climatic conditions were deduced from regional climate conditions (Vajda and Venäläinen 2003). The annual mean temperature is –0.8 °C, the winter mean temperature being about –11 °C and the summer mean temperature about 11.5 °C. The length of the frost-free period is about 75 days and the growing season is about 65 days. The mean annual precipitation is 580 mm and the maximum seasonal sum of precipitation occurs in summer.

In 1960 about 19 882 ha of vegetation was destroyed in the Tuntsa forest fire, of which 9307 ha was virgin forest, 5051 ha dwarf trees (krummholz) and 5524 ha was treeless area. Prior to the fire the area was covered by mature (>150 yrs) Norway spruce (*Picea abies* L. Karst.) forest intermixed with downy birch (*Betula pubescent* Ehrh.), but with Scots pine (*Pinus sylvestris* L.) dominating the stratified sand and gravel depos-
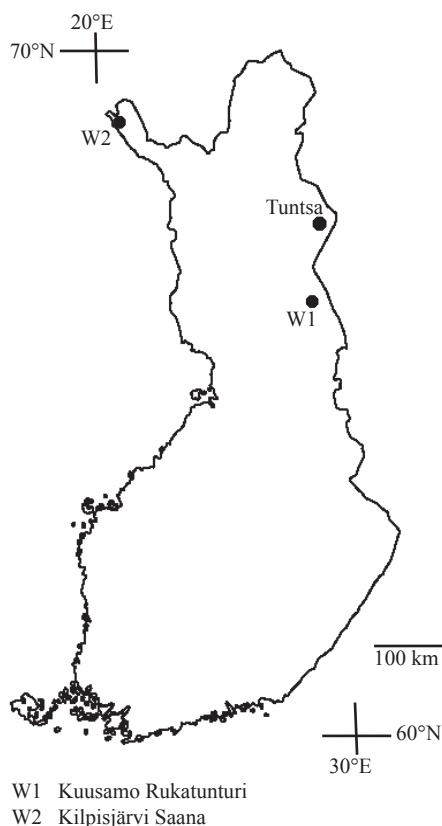

W1   Kuusamo Rukatunturi
W2   Kilpisjärvi Saana

Fig. 1. Location of the studied site in Lapland, northern Finland and of the stations used in the wind simulations.

its in the river valleys. The fire was widespread, but fire refuges, comprising stands dominated by spruce, were left in moist sites and in swales up to the tree-line (i.e. 460 m a.s.l.). After the fire, the area was intensively regenerated from 1961 with Scots pine by seeding, and later until 1976 by planting and mechanical site preparation. Despite a good start, the regeneration with pines failed on sites formerly covered by spruce. The natural regeneration of birch has been hampered by intensive reindeer grazing. The grazing pressure in winter and trampling in summer may cause severe reduction or even removal of vegetation structure in a sensitive arctic environment (Virtanen 2000, Cooper and Wookey 2003). Large areas are now treeless tundra with some patterned ground features. One of the fire refuges (67°38´N, 29°52´E)

covered by sparse Norway spruce stand intermixed with rich ground vegetation and its surrounding burned site covered by tundra-like vegetation were selected to study snow conditions in the forest and the surrounding treeless tundra.

2.2 Measurements, Models and Calculations

2.2.1 Snow Measurements

Snow depth and density were measured on a 1 km × 0.6 km site with a roughly uniform surface and two kinds of vegetation: forest, and treeless tundra vegetation (Fig. 2). The measurements were made during the second half of March 2003, characterized by the highest annual snow accumulation. The winter of 2002–2003 in Eastern Lapland was characterized by a mean snow cover of 50–70 cm that corresponds to the 1971–2000 mean snow depth (50–75 cm). Snow depth was determined manually (at 126 measurement points) and with radar. The manual measurement, which is the most commonly-used measurement method, was performed on six lines, 100 m apart and with a 50 m point spacing. At each observation point, three snow depth values were determined and the median of these was used in the analysis. In addition, snow density was measured at a few locations in both forested and treeless areas. On the basis of the density measurements, the water equivalent of the snow was calculated as follows:

$$W = 10 h_s \rho_s \tag{1}$$

where W is the water equivalent (mm), h_S is the snow depth (cm) and ρ_S is the snow density (g cm^{-3}).

Radar measurements were made using a SIR-2000 ground-penetrating radar with a 1000 MHz antenna (GSSI, North Salem, USA). The SIR-2000 unit was installed on a snowmobile that towed the antenna. It was estimated that the vehicle caused a 0–5 cm depression in the snow. The snow penetration of the selected antenna is up to two metres and the pulse length is only one nanosecond. The output scan frequency was synchronized using a survey wheel, allowing snow depth to be registered every 10 cm of horizontal distance. However, a 5-m interval was used in
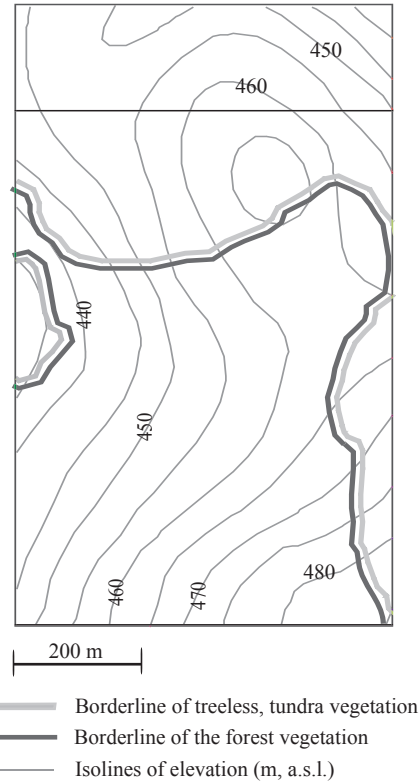

Fig. 2. The topographic map and the surface roughness of the studied area.

the snow depth analysis. The radar measurements followed the six survey lines. The manual snow thickness measurements were used in the calibration of the radar. Since the measurements were performed during one day, the calibration did not drift with time; neither local drift was observed, however in case of thin snow cover an absolute error occurred. The coordinates of the starting and ending points of each line were found using GPS equipment. The thickness of the snow cover obtained from the manual and radar measurements was analyzed in order to compare the results of these two measurement methods.

2.2.2 Wind Modelling

The spatial variation of snow depth depends on the vegetation as well as the orography. Vegeta-

tion influences the snow depth distribution in an indirect way, through its influence on the wind speed that depends on the roughness of the terrain and vegetation. Because wind is one of the most important factors in the snow accumulation process, knowledge of the wind climate is indispensable for an analysis of snow conditions. Due to the lack of wind measurements in the study area, the use of a wind simulation model was necessary. To estimate the spatial variation of wind velocity and direction we used the WAsP model (Wind Atlas Analysis and Application Program, Troen and Peterson 1989) that contains sub-models for orographic flow perturbations, roughness changes and the influence of obstacles on the wind field (Troen and Peterson 1989, Mortensen et al. 2000). The model has been used for the production of a wind atlas for several countries or larger areas, e.g. Troen and Peterson (1989) for Sweden, Reid (1997) for New Zealand, Frank and Landberg (1998) for Ireland, Bartholy and Radics (2001) for Hungary. WAsP has been used in Finland by Tammelin (1991) in the production of a wind atlas and Venäläinen et al. (2003) in the analysis of wind conditions over lakes. Based on a polar grid terrain representation, the orographic flow perturbations are evaluated as the sum of a spectral flow solution using a Fourier-Bessel expansion. For the vertical extrapolation to some new height above the surface in flat terrain with homogeneous roughness, a logarithmic wind profile is assumed. However, to account for the influence of non-neutral stratification, the logarithmic profile is perturbed. The homogeneous-terrain wind velocity is then modified by the mentioned terrain perturbations. All models depend on several parameters, which are described in Mortensen et al. (2000).

In order to describe the wind speed distribution, WAsP utilizes the *Weibull* distribution function (Tammelin 1991). The frequency of any wind speed is calculated by the *Weibull* probability function:

$$f(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} \exp\left[-\left(\frac{u}{A}\right)^k\right] \qquad (2)$$

where *f(u)* is the occurrence frequency of wind speed *u*.

The accumulation frequency of critical wind speeds larger than *u* is calculated using Eq. 3:

$$F(u) = \exp\left[-\left(\frac{u}{A}\right)^k\right] \qquad (3)$$

where *k* is the shape parameter describing the form of the distribution function and *A* is the scale parameter related to mean wind speed.

As background information for wind simulation the surface topography and roughness are needed. The height contours describing the topography of the area studied were obtained from a digital terrain map, using isolines at 5-m intervals. The surface roughness – that depends on the vegetation – was manually digitalized based on air photos and surface map data. Two categories were used: open field covered by small vegetation, bushes and shrubs (< 1.5 m high) with a roughness length of 0.2 m and forest (stands less than 12 m high) with a roughness length of 0.5 m (Tammelin 1991). The forest is relatively sparse, predominantly spruce with downy birch (*Betula pubescens*) as the subdominant species.

2.2.3 Simulations and Analysis

In order to estimate the wind climate of the region, the related synoptic wind measurements from two representative meteorological stations – Kuusamo Rukatunturi (66°10´N, 29°09´E, 486 m altitude) and Kilpisjärvi Saana (69°02´N, 20°51´E, 1007 m altitude) – for the period October 2002–March 2003 were used as input data. We selected these stations as input data taking into account primary criteria, such as geographical location, elevation and surroundings. These were the closest stations to our experiment area having roughly similar surroundings. Though the wind climate at these stations is not exactly the same as at our experiment area, these measurements give a somewhat good description of the wind climate. Based on this measured wind climate and using a 10 m × 10 m resource grid squares, we calculated the mean wind speed and wind speed distribution (*Weibull A and k*) at a height of 10 metres above the surface. For a more substantial analysis the mean wind speed was calculated for one location in the middle of

the study area at heights of 10 and 2 metres.

Based on the manual and radar snow measurements, maps giving the spatial distribution of snow depth were prepared using the kriging spatial interpolation method within the Surfer software (US Golden). Kriging was applied for the same 10 m × 10 m grid squares that were used in the wind simulations. Thus the snow depth of every grid-square was calculated, so the spatial distribution of snow depth could now be compared with surface characteristics, wind flow and vegetation types.

3 Results

3.1 Comparison of Snow Depth from the Two Different Measurements

In order to make the comparison of snow-depth values obtained with the two different measure-

ment methods as comprehensive as possible, the measurements (made manually in 126 locations and in 1130 locations by radar) were first interpolated onto the 10 m × 10 m grid and a comparison was made between the grid square values. Due to the higher frequency of the radar observations, measured at 5-m intervals, compared with that of the manual measurements (50 m) the radar provides a more detailed picture of the snow thickness. On a N-S transect the snow depth appeared to be smoothly distributed as measured manually, but more variable as measured by radar (Fig. 3). Due to its high resolution (10 cm), the radar is capable of detecting small variations in the ground, which affect the snow thickness at the respective location. However, the correlation (0.84) between the two datasets (Fig. 4) was significant. A comparison between manual and radar data for the six lines showed the correlation coefficients to be mainly above 0.90. The larger differences occur in the case of the first
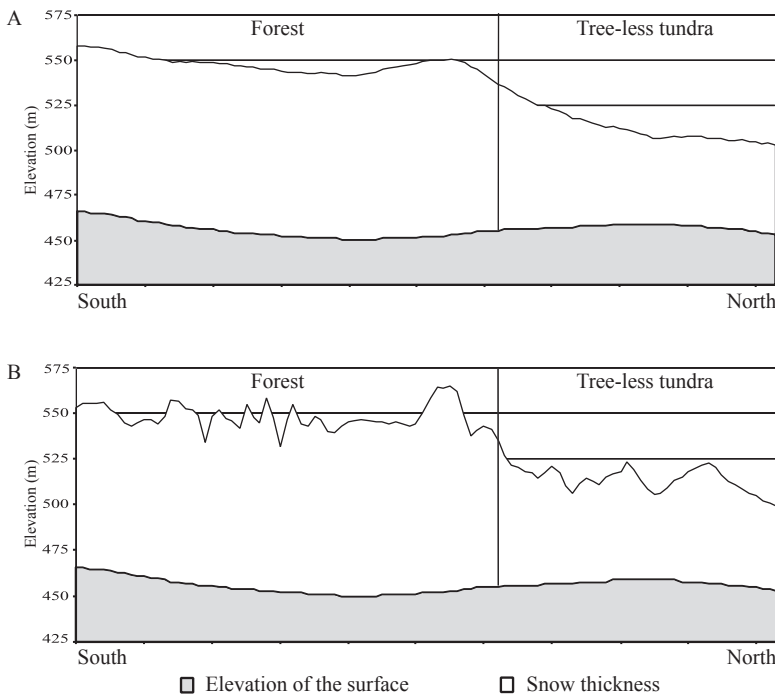

Fig. 3. Spatial variations in snow depth and topographic relief along a measurement transect from forest (in the south) to tundra vegetation (in the north): snow depth measured manually (A) and by radar (B).
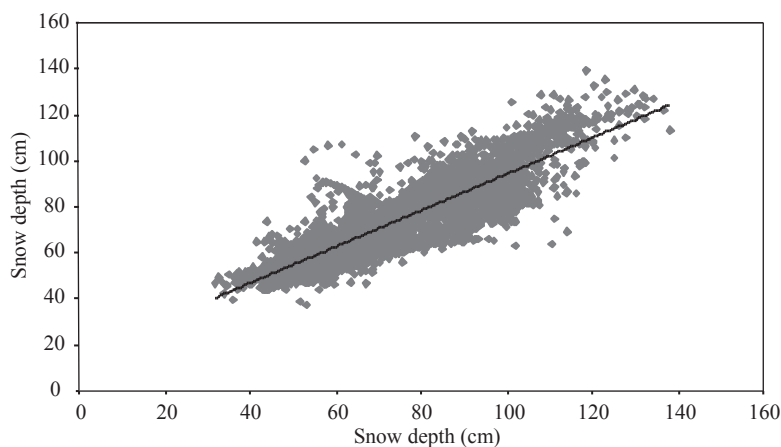
Fig. 4. Snow depth measured manually (x-axis) against that measured by radar (y-axis). In the comparison the snow-depth values obtained from the spatial interpolation of measured data were used.

two western lines: I – 0.75, II – 0.79, III – 0.92, IV – 0.96, V – 0.94, VI – 0.96.

According to the spatial variation of the differences between the manual measurement and radar values, the usual deviation is 5–15 cm, with larger values in the S and SE part of the western edge of the area studied (30–45 cm) and in some places in the transition between the forest and the open area. The radar measurements give a better depiction of the spatial variation of the snow cover than the manual ones, but on the other hand manual measurements can be regarded as being more precise in measurement location and thus we considered the use of both methods in the analysis as justified.

3.2 Wind Climate

The simulated wintertime, October–March, wind climate for Tuntsa indicates a mean wind speed of 3.9 m s^{-1} at a height of 10 metres above the surface. According to the wind rose, the most frequent (14%) simulated wind direction was from the sector 225–255 and the most frequent wind speed range, using a 1 m s^{-1} class interval, was 5–6 m s^{-1} (10.1%) (Fig. 5). The probabilities of high wind speed values, important in snow drifting, were examined with limits of 8 and 10
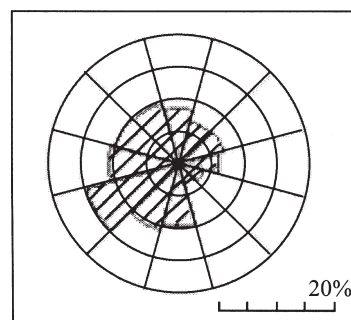

Fig. 5. The frequency distribution (%) of wind direction at the Tuntsa site at a height of 10 metres above the surface as estimated using WAsP.

m s^{-1} using the *Weibull* distribution. The mean probability for these high wind speed values was 4.7% for 8 m s^{-1} and 1.2% for 10 m s^{-1}. The most frequent wind direction calculated for the location in the middle of the area was same as that for the entire area. The simulated mean wind speed there at a height of 10 metres was 7.5 m s^{-1} and much less at 2 metres (4.0 m s^{-1}), where the roughness of the terrain reduces the wind speed.

The spatial distribution of the simulated average wind speed (Fig. 6) is mainly influenced by the surface roughness. Though, the elevation of
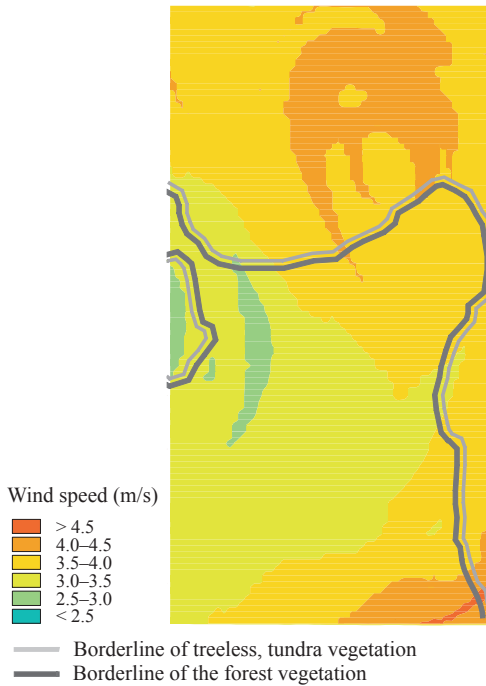
Wind speed (m/s)

> 4.5
4.0–4.5
3.5–4.0
3.0–3.5
2.5–3.0
< 2.5

― Borderline of treeless, tundra vegetation
― Borderline of the forest vegetation

Fig. 6. The spatial distribution of simulated mean wind speed on the studied site.

the study area does not vary much (maximum 20 m; Fig. 2), it can cause small changes in the distribution of wind speed. A strong mean wind (3.5–4 m s⁻¹) is frequent over the open area, with the highest value (4.5 m s⁻¹) in these locations and in the south-east. Over the transition between the forest and the open area the wind speed is higher as well, as consequence of winds from the northern and eastern sectors, which only decrease gradually over the surface with a higher roughness. The change in the elevation, i.e., the higher altitude in the middle of the region compared with the eastern part, could contribute to the higher speed values in this area. In the western and southern parts of the region a lower wind speed dominates (2.5–3.5 m s⁻¹), with the minimum values being found in the western part of the forest due to the roughness and topography.

3.3 The Spatial Distribution of Snow Cover

Based on the measurements (manual and radar), the mean snow depth in the study area was 77 cm, the maximum 140 cm and the minimum 30 cm.
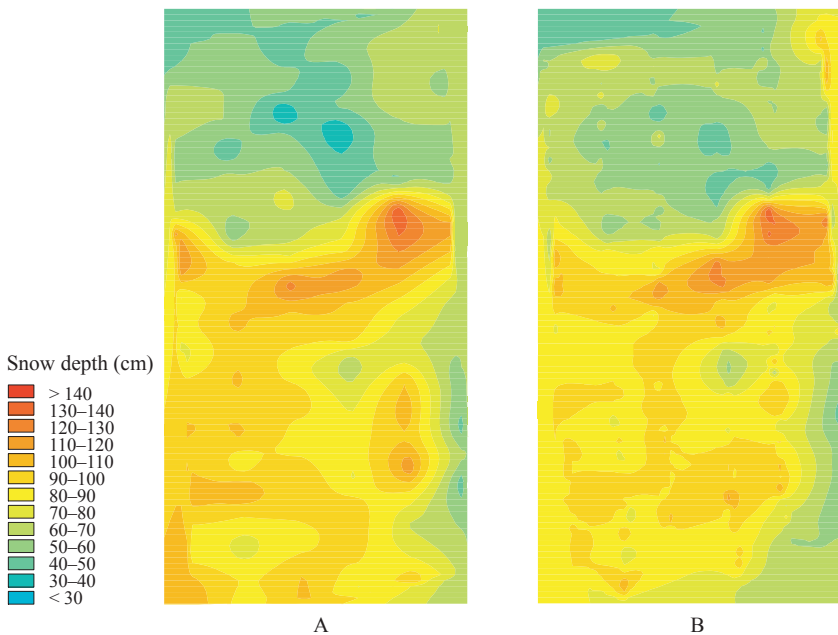

Snow depth (cm)

> 140
130–140
120–130
110–120
100–110
90–100
80–90
70–80
60–70
50–60
40–50
30–40
< 30

A   B

Fig. 7. Snow-depth distribution based on the manually measured data (A) and radar data (B).
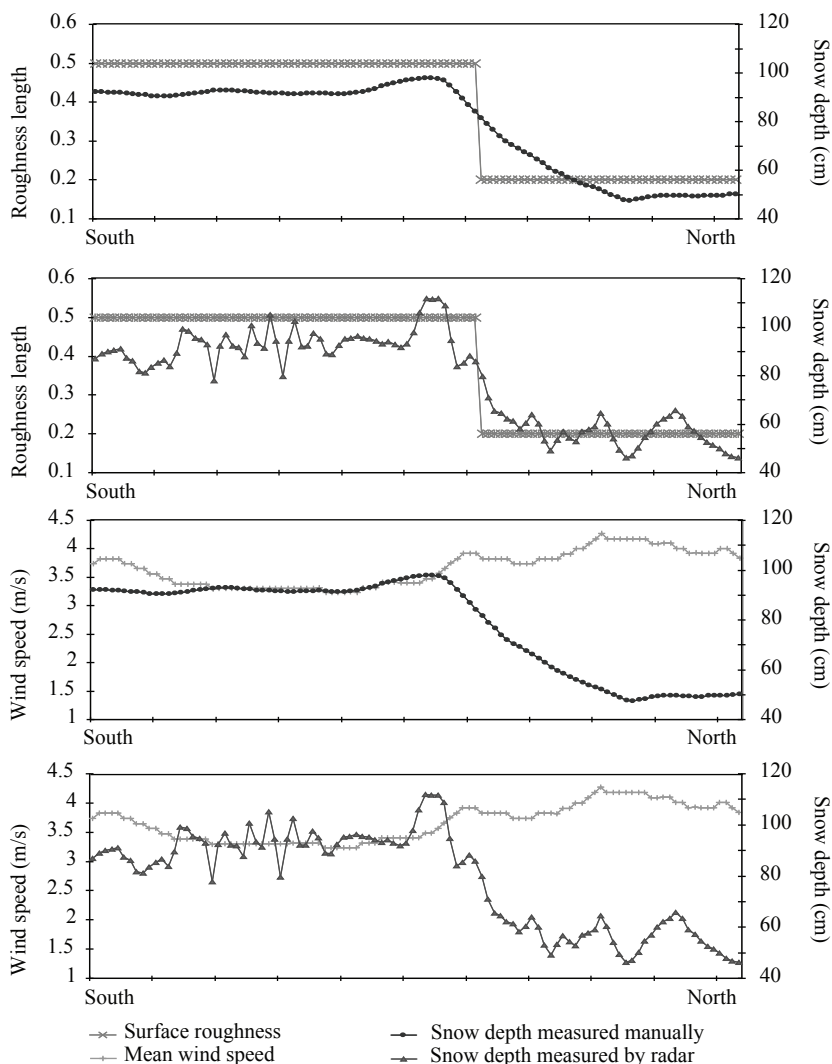
Fig. 8. The spatial variation of the surface roughness, mean wind speed and snow depth along a cross-section from forest (S) to tundra vegetation (N).

The snow depth values obtained from the interpolated values for the 10 m × 10 m grid boxes demonstrate that the vegetation type and wind velocity had the most pronounced influence on the spatial distribution of snow depth, the linear regression coefficients being 0.90. Of the contributing factors, vegetation had the most decisive influence on the snow depth (correlation coefficient: 0.87). The effects of wind velocity and elevation were smaller, the respective correlation coefficients

being 0.66 and 0.17. The low correlation between the elevation and snow cover in the present case could be explained by the almost flat topography, the maximum variability of the isolines being only 20 m.

The distribution of snow cover (Fig. 7) indicates the lower snow depths (40–70 cm) in the northern zone and on the eastern edge of the area studied, coinciding with the open area covered by tundra vegetation (see Fig. 2). Within these,

the lowest values (30 cm) are found in the part with the highest wind speed (see Fig. 6). In the forest – where the wind speed is lower and thus also drifting of the snow – the snow accumulation was greater, 70–120 cm. The largest snow depths (130–140 cm) were found in the transition between the forest and the open area, where the snow accumulated from snowfall and a large amount was transported and deposited by the wind. Inside of the forest the snow depth showed a uniform distribution.

In the analysis of snow distribution, we illustrated the variation of snow, vegetation (as surface roughness) and wind speed on a representative S-N cross-section (Fig. 8) taking into account all the grid-square values. The significant changes (30 cm) in the snow thickness followed the change in the vegetation type and roughness values respectively. The snow curve reached its maximum (100 cm) inside the forest edge, after which it moderately declined towards the open area. The wind-snow relation showed the same pattern. In the southern and northern parts of the section, where the wind speed was higher, the snow depth was lower.

A Snow depth measured manually
B Snow depth measured by radar

Fig. 9. The depth of snow-cover in the forested area and the open, tree-less area. The horizontal line within the box corresponds to the median and the end of the box to the interquartile range, the "whiskers" give extreme values within –1.5 and 1.5 times the interquartile range. Values outside –1.5 and 1.5 times the interquartile range are shown with circle.

4 Discussion

The main aim of the study was to analyze the small-scale variability of the snow cover and the influence of topography, wind and vegetation types on the snow depth on an experimental site in Finnish Lapland (Tuntsa). In addition, manual and radar snow measurements were analyzed to compare the results of these measurements methods. The results of this analysis indicate some differences between the snow depth measurements. Although the box-plot density analysis of snow-depth (Fig. 9) showed the same average for the manual and radar measurements, the more extreme values were more scattered, with large differences between the maximum values.

In general, the environmental changes associated with a fire-induced shift of the tree line are considerable. Our results indicate that the distribution of snow accumulation varied in relation to the type of vegetation and wind velocity, while the influence of elevation was less demonstrable,
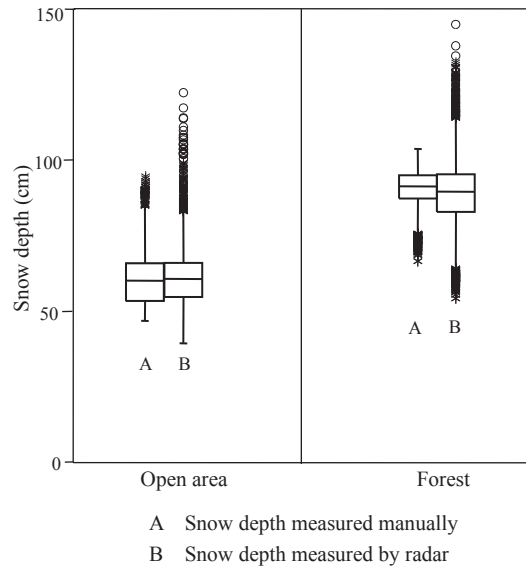
because of the flat features of the experimental site. The snow cover turned out to be significantly less in the open tundra area compared to that in forest (Fig. 7). In the open area, small vegetation, composed of grass and shrubs, allows a higher wind flow velocity and thus more vigorous snow drifting. In the spruce forest, where the possibilities of redistribution of the snow by wind flow were limited, the snow accumulation was higher on average by 30 cm. However, the difference in the mean wind speed (0.4 m s^{-1}) over the two distinct vegetated surfaces can not be the explanation for the differences in snow cover; the mean probability of high wind speeds was the factor that produced the large deviation in snow depth, the probability of 8 m s^{-1} and 10 m s^{-1} wind speeds being almost twice as high in the open area (6.1% and 1.8%) than in the forest (3.8% and 0.9%). In similar conditions in Canada (northern Québec) to those of the studied site, the snow cover showed

Table 1. The average snow depth, elevation and mean wind speed in the open area with tundra vegetation and in the forest.

| | Mean snow depth (cm) | | Maximum snow depth (cm) | | Minimum snow depth (cm) | | Standard deviation | Elevation (m) | Wind speed (m s⁻¹) |
	Manually	Radar	Manually	Radar	Manually	Radar			
Open area	61.1	61.6	94.3	121.9	46.8	39.1	9.6	456.2	3.9
Forest	89.9	88.9	103.3	144.5	66.2	53.9	6.2	456.5	3.5

a 20–40 cm decrease in the deforestation zone (Arseneault and Payette 1992); the zone was probably caused by a post-fire exclusion of conifers and by the substitution of those by lichen-tundra vegetation unable to trap drifting snow.

A distinct snow-depth category was the forest edge, where the snow transported by winds from the direction of the open area had been deposited, creating the highest snow thickness. The presence of larger snow depths in forest openings or at the boundaries between covered and exposed areas may often occur. This excess is due to the deposition of snow originally retained by the canopy and blown off by the wind (Kuusisto 1984).

The mean, maximum and minimum snow thicknesses calculated using all the grid squares from the entire study area displayed significant differences for the two separate vegetation types (Table 1). Even though the elevation and mean wind speed were almost equal for the two types of surface, there was a large variation – 30 cm for the mean, 20 cm for the maximum and 10 cm for the minimum snow depth – between the tundra and forest vegetation. The box-plot density analysis (Fig. 9) showed similar features for the distribution of snow thickness.

The density and the water equivalent of snow may also depend on the type of vegetation. However, according to our results, the snow density does not vary significantly between the two vegetation types; the average of the snow density was 2.6 g cm⁻³, with similar mean values in forest and on open area. Even so, the average water equivalent in the forest (2256.6 mm) was almost double of that in the open area (1229.7 mm). These results indicate a much higher difference in water equivalent in comparison with earlier studies (Seppänen 1961), which indicated about the same values for the water equivalent of an open area and a pine forest in the latitude zone 64–70° N. The reason for the difference between the water equivalents is the thinner, more packed snow cover in the open areas than in the forest (Kuusisto 1984).

The interaction between snow and vegetation has two aspects. First, the influence of the vegetation on the distribution of snow accumulation has been discussed above. In addition, the influence of the snow cover on the vegetation may not be ignored. The snow cover impacts on the ecological and hydrological processes throughout the year (Liston et al. 2002). The accumulation of snow and the microclimatological conditions induced by the variations in snow cover and local meteorological conditions (radiation, temperature, evaporation and wind) cause differences in growth conditions. Deep, insulative snow assures greater protection from winter desiccation and wind abrasion, reduces the frost activity and increases the snowmelt runoff and summer soil moisture (Seppänen 1961, Sturm et al. 2001). Our study does not consider the variation in radiation budgets and temperature, but according to former studies (Wein and Bliss 1973, Harding and Pomeroy 1996) there are radical differences between the energy balance of forested and nonforested areas. The melting process in the forest occurs later than on the open area because of the shading by the trees. The above-mentioned properties of the snow cover affect the growth of plants and the regeneration of vegetation in the impacted region.

On the other hand, snow could give plants protection against the large number of reindeer – 12 080 a year (Kemppainen et al. 2001) – that are herded in the Tuntsa region. Reindeer grazing and trampling causes negative feedback on the vegetation; it may change the vegetation into

dwarf shrubs, even leaving only bare soil (den Herder et al. 2003) and may preclude the regeneration of the forest. The plant biomass in a low productivity arctic-alpine snowbed may be reduced and the accumulation of plant litter may be prevented by grazing (Virtanen 2000). Deep snow, e.g., in forested areas, causes reindeer difficulties in reaching their food, which usually consists of lichens, undergrowth and plant shoots. In the unforested area, where snow drifting is more accentuated and the snow accumulation is lower, reindeers significantly retard or even prevent the regeneration of vegetation.

5 Conclusions

This study focuses on the influence of vegetation on the small-scale spatial variability of snow cover near the timberline in Finnish Lapland, and on the implications that the variation of snow cover have for forest regeneration preconditions. Our case study indicates a strong dependency of snow distribution on vegetation type and wind velocity and direction. Snow drifting is much more vigorous in open areas, where, following the fire in the 1960's, tundra vegetation evolved, than in the forested landscape. In the affected region near the northern timberline, any changes in surface conditions may create negative feedbacks, which prevent or retard the returning of the vegetation to its original state. The reduced snow cover results in more unfavourable climatic and soil conditions for the recovery of the forest, even permitting reindeer to inflict damage on the regenerated vegetation. To get a better understanding of those feedback mechanisms operating between the atmosphere, soil and vegetation that are relevant at the northern timberline, more meteorological measurements and modelling work are needed.

Acknowledgements

References

Arseneault, D. & Payette, S. 1992. A postfire shift from lichen-spruce to lichen-tundra vegetation at tree line. Ecology 73(3): 1067–1081.

Bartholy, J. & Radics, K. 2001. Selected characteristics of wind climate and the potential use of wind energy in Hungary. Part I. Idõjárás 105(2): 109–126.

Clark, M.J., Gurnell, A.M., Milton, E.J., Seppälä, M. & Kyöstilä, M. 1985. Remotely-sensed vegetation classification as a snow depth indicator for hydrological analysis in sub-arctic Finland. Fennia 163: 195–216.

Cooper, A.J. & Wookey, P.A. 2003. Floral herbivory of Dryas octopetala by Svalbard reindeer. Arctic, Antarctic and Alpine Research 35(3): 369–376.

Daly, C. 1984. Snow distribution patterns in the alpine krummholz zone. Progress in Physical Geography 8: 157–175.

Frank, H.P. & Landberg, L. 1997. Modelling the wind climate of Ireland. Boundary Layer Meteorology 85: 359–378.

Gustafsson, D., Stähli, M. & Jansson, P.E. 2001. The surface energy balance of a snow cover: comparing measurements to two different simulation models. Theoretical and Applied Climatology 70: 81–96.

Harding, R.J. & Pomeroy, J.W. 1996. The energy balance of the winter boreal landscape. Journal of Climate 9: 2778–2787.

— , Gryning S.E., Halldin, S. & Lloyd, C.R. 2001. Progress in understanding of land surface/atmosphere exchanges at high latitudes. Theoretical and Applied Climatology 70: 5–18.

Herder den, M., Kytöviita, M.M. & Niemelä, P. 2003. Growth of reindeer lichens and effects of reindeer grazing on ground cover vegetation in a Scots pine forest and a subarctic heathland in Finnish Lapland. Ecography 26: 3–12.

Hustich, I. 1979. Ecological concepts and biographical zonation in the North: the need for a generally accepted terminology. Holarctic Ecology 2: 208–217.

Kemppainen, J., Kettunen, J. & Nieminen, M. 2001. Poron taloudellinen hyödyntäminen. Esiselvitys. [Online document]. Kala- ja riistaraportteja 237. 27 p. Available at: http://www.rktl.fi/www/uploads/pdf/raportti237.pdf. (In Finnish).

Koivusalo, H., Heikinheimo, M. & Karvonen, T. 2001. Test of a simple two-layer parameterisation to

simulate the energy balance and temperature of a snow-pack. Theoretical and Applied Climatology 70: 65–79.

Koskinen, J., Metsämäki, S., Grandell, J., Jänne, S., Matikainen, L. & Hallikainen, M, 1999. Snow monitoring using radar and optical satellite data. Remote Sensing and Environment 69(1): 16–29.

Kuusisto, E. 1984. Snow accumulation and snowmelt in Finland. Publications of the Water Research Institute 55. Helsinki. 149 p.

Lee, S.E., Press, M.C., Lee, J.A., Ingold, T. & Kurttila, T. 2000. Regional effects of climate change on reindeer: a case study of the Muotkatunturi region in Finnish Lapland. Polar Research 19(1): 99–105.

Liston, G.E., McFadden, J.P., Sturm, M. & Pielke, R.A. 2002. Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs. Global Change Biology 8: 17–32.

Lloyd, C.R., Harding, R.J., Friborg, T. & Aurela, M. 2001. Surface fluxes of heat and water vapour from sites in the European Arctic. Theoretical and Applied Climatology 70: 19–33.

Lynch, A.H., Bonan, G.B., Chapin III, F.S. & Wu, W. 1999. Impact of tundra ecosystems on the surface energy budget and climate of Alaska. Journal of Geophysical Research 104(D6): 6647–6660.

Mortensen, N.G., Heathfield, D.N., Landberg, L., Rathmann, O., Troen, I. & Petersen, E.L. 2000. Getting started with WAsP7. Risø National Laboratory, Roskilde, Denmark. 50 p.

Press, M.C., Potter, J.A., Burke, M.J.W., Callaghan, T.V. & Lee, J.A. 1998. Responses of a subarctic dwarf shrub health community to simulated environmental change. Journal of Ecology 86: 315–327.

Pruitt, W.O. 1979. A numerical snow index for reindeer (Rangifer. tarandus) winter ecology (Mammalia, Cervidae). Annales Zoologici Fennici 16: 271–280.

Reid, S. 1997. Modelling of channelled winds in high wind areas of New Zealand. Weather and Climate 17: 3–22.

Scott, P.A. & Rouse, W.R. 1995. Impacts of increased winter snow cover on upland tundra vegetation: a case example. Climate Research 5(1): 25–30.

Seppänen, M. 1961. On the accumulation and the decreasing of snow in pine dominated forest in Finland. Fennia 86(1). 51 p.

Solantie, R., Drebs, A., Hellsten, E. & Saurio, P. 1996. Timing and duration of snow cover in Finland 1961–1993. Finnish Meteorological Institute Publications 34. 159 p.

— 2000. Snow-depth on January 15th and March 15th in Finland 1919–98, and its implications for soil frost and forest ecology. Finnish Meteorological Institute, Meteorological Publications 42. 176 p.

Sutinen, R., Teirilä, A., Pänttäjä,M. & Sutinen, M.L. 2002. Distribution and diversity of tree species with respect of soil electrical properties in Finnish Lapland. Canadian Journal of Forest Research 32: 1158–1170.

Sturm, M., McFadden, J.P., Liston, G.E., Chapin III, F.S., Racine, C.H. & Holmgren, J. 2001. Snow-shrub interactions in arctic tundra: a hypothesis with climatic implications. Journal of Climate 14: 336–344.

Tammelin, B. 1991. Suomen tuuliatlas. Finnish Meteorological Institute, Helsinki. 355 p.

Troen, I. & Peterson, E.L. 1989. European wind atlas. Risø National Laboratory, Roskilde, Denmark. 656 p.

Vajda, A. & Venäläinen, A. 2003. Small-scale spatial variation of climate in Finnish Lapland. Finnish Meteorological Institute Reports 2003(1). 34 p.

Venäläinen, A., Sahlgren, V., Podsechin, V. & Huttula, T. 2003. Small-scale variability of the wind field over a typical Scandinavian lake. Boreal Environmental Research 8: 71–81.

Virtanen, R. 2000. Effects on above-ground biomass on a mountain snowbed, NW Finland. Oikos 90: 295–300.

Wein, R.W. & Bliss, L.C. 1973. Changes in arctic Eriophorum tussock communities following fire. Ecology 54(4): 845–852.

Total of 35 references