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Temporal and Spatial Occurrence of Strong Winds and Large Snow Load Amounts in Finland during 1961–2000

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Information on the temporal and spatial occurrence of strong winds and snow loads on trees is important for the risk management of wind- and snow-induced damage. Meteorological measurements made at 19 locations across Finland during 1961–2000 are used to understand the temporal and spatial occurrence of strong winds and large snow loads. A Kriging interpolation method was used to produce a spatial analysis of wind-speed events above 11 $m\,s^{-1}$, 14 $m\,s^{-1}$, and greater or equal to 17 $m\,s^{-1}$ and snowfall accumulation above 20 $kg\,m^{-2}$ and 30 $kg\,m^{-2}$. According to the analysis, wind speeds exceeded 14 $m\,s^{-1}$ at least 155 times and reached 17 $m\,s^{-1}$ only 5 times at inland locations during the 40 years. Large snowfall accumulations were more frequent in the higher-elevation inland areas than along the coast. The snow load on trees exceeded 20 $kg\,m^{-2}$ about 65 times a year when averaged over all 40 years, but was as high as 150 times a year during the mild 1990s. The maximum number of heavy snow-load events occurred in 1994 in northern Finland, consistent with a forest inventory by the Finnish Forest Research Institute in 1992–1994. The findings of this study imply that the risk of wind-induced damage is highest in the late autumn when trees do not have the additional support of frozen soil. In contrast, the risk of snow-induced damage is highest at higher-elevations inland, especially in northern Finland.

Keywords coniferous forest, wind climate, precipitation, soil frost, snow
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Erratum (23 Oct 2012): The authors have requested inclusion of an additional author. Author information should thus be:

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1 Introduction

Wind and snow damage are the most significant threats to forestry in northern and central Europe (e.g., Quine 1995, Nykänen et al. 1997). For example, on 25 January 1990, 100 million m^3 of timber was blown down in Europe on a single stormy night (e.g., Dobbertin 2002, Schönenberger et al. 2002). Similarly, on 26–28 December 1999, catastrophic winds (Ulbrich et al. 2001) blew down 175 million m^3 of timber in Europe (Brüdl and Rickli 2002, Wernli et al. 2002, Cucchi and Bert 2002). Two storms in November 2001 (1 and 15–16) caused widespread wind- and snow-induced damage in Finland, resulting in the loss of 7 million m^3 of timber (e.g., Pellikka and Järvenpää 2003). The storm of 8 January 2005 (Alexandersson 2005) caused massive destruction to the forests of Sweden (about 70 million m^3 of timber), but spared Finland.

Common forms of forest damage caused by wind and snow are the uprooting of trees (especially in unfrozen soil when additional support for the roots is lacking), stem breaking, and stem bending or leaning (e.g., Solantie 1994, Everham 1995). Other damage can occur to the canopy, consisting of branch loss, canopy defoliation, and destruction (e.g., Zhu et al. 2002). Stand quality can be further reduced because damaged trees are more tempting to insect and fungi attacks (e.g., Nykänen et al. 1997, Valinger and Fridman 1997, Schönenberger et al. 2002). The Finnish Forest Research Institute surveyed the occurrence of damaging agents reducing stand quality in Finland during 1986–1994 (Metsätilastollinen vuosikirja 1999). The inventory started from southern Finland in summer 1986 and reached northern Finland in 1992. Northern Finland was further surveyed during summers 1992, 1993 and 1994. According to the inventory, 1.2% of the forest land area in Finland was damaged by wind and 2.3% was damaged by snow. In Lapland the area affected by damaging agents such as wind, snow, other climate factors (e.g., frost, drought and fire), competition, harvesting damage, moles, elk, insects, and fungi during 1993–1994 was estimated to be 28.5% of the total forest land area of Lapland. Of that amount of forest land area, approximately one quarter had been damaged by snow, more than one third by fungi, and one tenth by wind.

The susceptibility of stands to wind and snow damage is also dependent on tree and stand characteristics (e.g., tree species, stand density, tree characteristics, soil type) that are controlled by forest management (Coutts 1986, Laiho 1987, Lohmander and Helles 1987, Peltola et al. 1999b, Schönenberger et al. 2002, Zhu et al. 2003b, Zhu et al. 2006). For instance, trees in northern Finland, such as narrow crowned spruce (*Picea abies* subsp. *obovata* (Ledeb.)), have evolved to tolerate higher snow loads (e.g., Peltola et al. 1999b). The risk of wind- and snow-induced damage is often highest at sudden changes in the exposure of trees – for example, new forest edges with trees unacclimated to strong winds or where large snow loads lie on unthinned dense stands (e.g., Alexander 1964, Neustein 1965, Persson 1972, Laiho 1987, Peltola 1996a,b, Gardiner and Stacey 1995, Gardiner and Quine 2000, Pellikka and Järvenpää 2003). The risk of damage to forests varies due to local meteorological and climatological effects (e.g., Valinger et al. 1993, Nykänen et al. 1997, Peltola et al. 1999a, Yli-Kojola 2002, Pellikka and Järvenpää 2003), implying that any attempt to develop suitable management practices to reduce the risk of damage also requires spatial information on wind and snow extremes.

To date, only a few studies concentrating on the return periods of snow- and wind-induced damages in the forests of Finland exist, and those results are based on case studies, not on long time series. Solantie (1994) determined that slight snow damage in forests occurs when liquid water equivalent of precipitation totals 30–39 mm in five days and moderate snow damage occurs when liquid water equivalent totals 40–59 mm in five days. Consequently, low and moderate snow damage has an expected return period every fifth year in southern Finland and every third year in north-eastern Finland in recent years, whereas in western and central Finland (excluding some regions at higher elevations), the return period is once or twice in 20 years (Solantie 1994). Averaged over Finland, Päätalo (2000) found that liquid water equivalent of precipitation of 30–39 mm occurs 8.3 times in 10 years but snow-induced damage on trees only 1.3 times in 10 years. An estimate for snow loads causing stem breakage is 54–60 $kg\,m^{-2}$ in managed stands and 10–25 $kg\,m^{-2}$ in unmanaged stands when the age of the

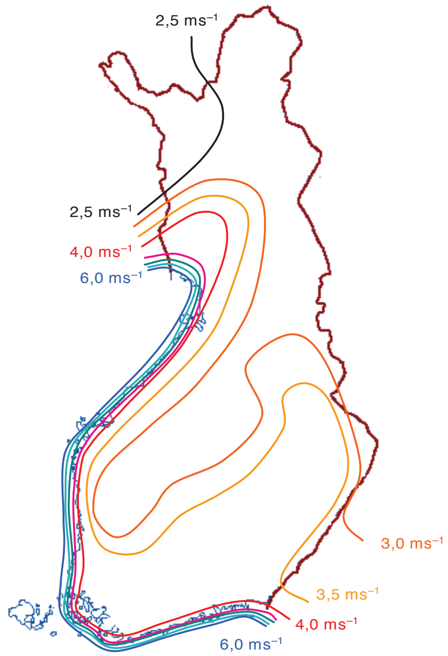


Fig. 1. Average 10-minute wind speeds spatial distribution in inland and coastal area during October-March in 1971–2000 in Finland drawn based on wind statistics of Finland (Drebs et al. 2001). The isolines begin with 2.5 m s^{-1} (black) and increase by 0.5 m s^{-1} intervals up to 6 m s^{-1} (blue).

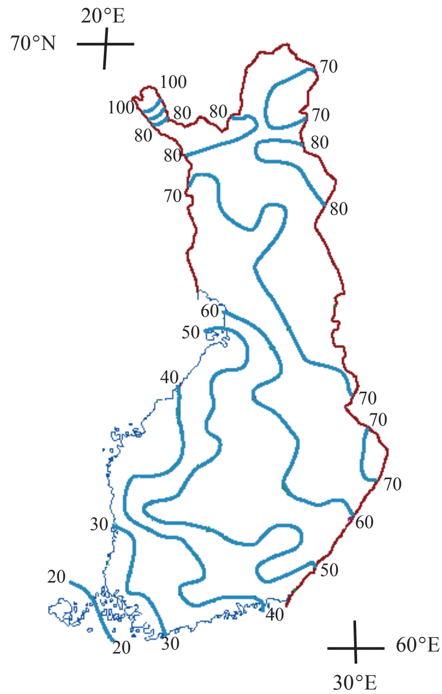


Fig. 2. Mean annual maximum snow depth (cm) during 1961–1990 (based on Huttunen and Soveri 1993).

trees in a coniferous forest is between 30–100 years (Päätalo 2000). Similarly an estimate for snow loads causing uprooting is 17–53 kg m^{-2} in managed stands and 10–23 kg m^{-2} in unmanaged stands in a coniferous forest when the age of the trees is between 30–100 years (Päätalo 2000).

In general, large differences in the risk of wind- and snow-induced damage occur across Finland according to their topography, climate, and weather. Even relatively low wind speeds when coupled with heavy snow loads can cause significant damage (Laiho 1987, Talkkari et al. 2000, Pellikka and Järvenpää 2003). For example, wind damage to forests often occurs near the sea and large lakes where the wind speeds are higher due to the reduced surface roughness relative to the surrounding land surface. In Finland, wind speeds 11–13 m s^{-1} can cause damage to forests, with much greater destruction when the wind exceeds 14 m s^{-1} (e.g., Solantie 1983, 1986, Peltola et al. 1999, Päätalo 2000). In contrast, snow-induced damage is most likely when the air temperature is between –3° and +0.6 °C and the winds are light (e.g., Solantie 1983, 1986, 1994, Valinger and Lundqvist 1994, Päätalo 2000, Quine 2000) because the accumulation of snow and deposition of hoar frost (when saturated) to the trunks and branches of the trees is most effective. Such conditions most likely occur inland within central and northern Finland, where the winds are weaker (Fig. 1) and the number of days with maximum temperature above 0 °C during December–March is smaller than anywhere else in Finland (Alalammi 1987, Drebs et al. 2001).

The common features of winter climate of Finland are presented in Fig. 2 and 3. In Fig. 2 is the mean annual maximum snow depth (cm) during 1961–1990. The locally higher elevations of southern and western Finland receive somewhat higher snow fall amounts than the surroundings.

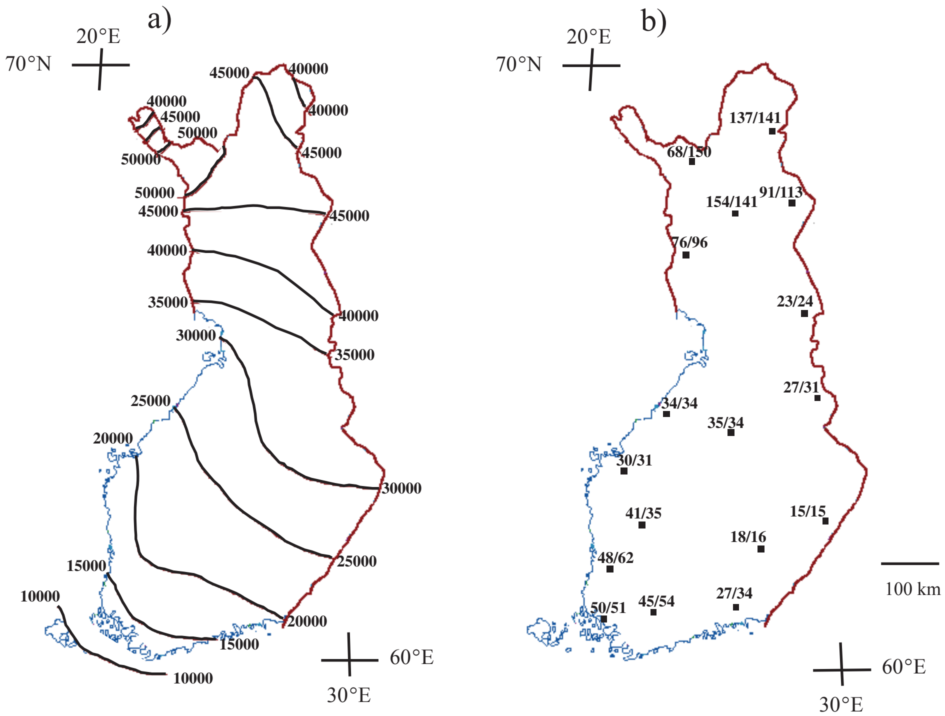


Fig. 3. a) Mean annual frost sum (h°C) during 1971–1990 (Huttunen and Soveri 1993) and b) mean annual maximum soil frost depths (cm) in the open countryside/forest during 1961–1990 (Huttunen and Soveri 1993).

But on average the largest snow depths are most common in the eastern most Finland and Lapland. The mean annual maximum frost sum in h°C (Fig. 3) according to Huttunen and Soveri (1993) increases remarkably from south-western Finland (10 000 h°C) towards eastern and northern Finland (30 000–50 000 h°C). Despite of the differences in frost sum between south-western Finland and eastern Finland the frost depths (cm) in open countryside and forest behave in the opposite way (Fig. 3). In the east close to the lakes and dense forests the mean annual frost depths have varied between 15–34 cm and in the west 35–62 cm. In Lapland the mean annual maximum frost depths have been above 140 cm during 1961–1990.

Under a future warmer climate, the risk of wind damage in Finland will likely increase with a longer period of unfrozen soil (Peltola et al. 1999a). One estimate of the future soil frost-depth changes in Finland is presented by Venäläinen et al. (2000), who used the Hadley Centre (UK Met. Office) global ocean–atmosphere general circulation model (HadCM2) down-scaled with the regional climate model at the Rossby Centre (SMHI, Sweden). They found that the average annual maximum soil frost depth in Finland decreases 50–75% by 2100.

Under a future warmer climate, the risk of snow damage in Finland will likely vary in time and location. The amount of winter precipitation is predicted to increase by about 20% in Finland under a warmer climate (e.g., Räisänen and Joelsson 2001, Räisänen et al. 2003, 2004, Ruokolainen 2005, Räisänen 2008). If the increase in precipitation happens simultaneously with the temperature range –3° to +0.6 °C becoming more frequent, the risk of snow-induced damage could increase, at least for a while. At the same time, the amount of winter precipitation increases, the amount falling as snow will decrease: 20% by 2100 over Finland as a whole, and 40–70% in southern and central Finland (Ruokolainen 2005). Therefore, the risk of snow-induced damage seems to be largest in the near future, decreasing by 2100. However, in some simulations, the daily snowfall amounts may even increase (Ruokolainen 2005), further exposing trees to large snow loads. Finally, future changes in snow depth in northern Finland are expected to be slow (Ruosteenoja et al. 2005), and, therefore, the risk of snow-induced damage in the north could remain steady or even increase during this century.

The main objectives of this paper are 1) to present the temporal and spatial occurrence of strong wind in Finland based on meteorological data measured during 1961–2000 at 19 stations operated by the Finnish Meteorological Institute (FMI), 2) to estimate the temporal and spatial distributions of wind-induced damage to forests, and 3) to present a new method for estimating the snow-induced damage based on cumulative snow-load calculations. The findings of this study are compared with previous work and are discussed within the context of future climate change.

Fig. 4. All 19 stations used in this research.

2 Material and Methods

2.1 Data and Meteorological Measurements

The data used in this study are the 10-minute-average wind speed (U) and 2-m air temperature (T), both measured every 3 h, and 12-h liquid water equivalent of precipitation (prec) during 1961–2000. This data originates from the meteorological observing network operated by FMI. Many changes in the network have occurred during these 40 years, so using the database for climatological research can be challenging. For instance, since 1966, over 400 daily precipitation measurements are available in the database, whereas, before 1966, only 100–200 stations are available (Venäläinen et al. 2005). In the 1980s, all FMI rain gauges (Wild) were changed to gauges (Tretjakov) capable of measuring the snowfall better (e.g., Sarkanen 1989). Missing data also exists in the database. Therefore, to ensure quality, a check of the data availability, quality, and continuity was made, reducing the dataset to only 19 stations, mostly airport weather stations (Fig. 4). Even some of these 19 stations had data discontinuities. For example, the height of wind measurements was changed at several stations (Table 1), and some months lacked precipitation observations (Table 2). As a result, some corrections to the data were made, described in the next section.

2.2 Methods Used to Homogenize the Wind Observations and to Calculate the Share of Strong Wind Speeds during Frozen Soil

To standardize the 10-minute-average wind speeds made at different heights to a uniform 10-m height, the logarithmic profile of wind speed with height (Holton 1992, p. 132) was used:

$$U(z) = \frac{U*}{k} \ln \frac{z}{z_0} \tag{1}$$

where U is the wind speed (m s^{-1}) at height z (m), $u*$ is the friction velocity (m s^{-1}), k is the von

Table 1. Stations used in this work and values used in wind corrections. Stations marked by a star are airport weather stations. Roughness mean value for each station during 1961–1990 presented in column z_0 is based on wind atlas of Finland (Tammelin 1991). Height of wind measurements and previous changes are marked in column Changes. Other remarks refer to changes in observation frequency.

Station	Name	z_0	Height (m)	Changes	Other remarks
301	Helsinki-Vantaa*	0.12	10		
501	Kotka-Rankki	0.08	19		
1001	Pori*	0.05	10	1.1.1961–1.11.1990 20 m, –1.1.1999 19.5 m	
1101	Turku*	0.4	10	1.1.1961–22.7.1987 13 m; –15.11.1990 20 m; –1.1.1991 16 m; –1.1.1999 16.2 m	
1201	Jokioinen obs.	0.7	30		
1501	Utti*	0.25	12	1.1.1961–9.10.1994 10 m	
2101	Kankaanpää	0.7	17	1.1.1961–15.12.1995 22 m; –23.1.1997 14 m; –2.12.1999 15 m	
2401	Jyväskylä*	0.25	10		
3003	Mustasaari	0.001	18	1.1.1961–1.5.1984 10 m; –1.11.1984 7 m	
3201	Kauhava*	0.25	16	1.1.1961–1.1.1999 10 m	
3601	Kuopio*	0.25	12	1.1.1961–8.12.1999 10 m	
3801	Joensuu*	0.23	10		1996/97 lack of obs 21 UTC and 00 UTC; 1998 lack of obs 21, 00, 03 UTC
4601	Kajaani*	0.25	12	1.1.1961–1.12.1991 10 m	
5401	Oulu*	0.25	10	1.1.1961–25.9.1991 16 m	
6801	Kuusamo*	0.4	10	1.1.1961–1.7.2000 12 m	
7401	Rovaniemi*	0.09	11	1.1.1961–1.6.1987 10 m	
7501	Sodankylä obs.	0.98	22		
8201	Muonio	0.5	12		1961 observations every 6 hours, 1982/83 lack of 6 months
9601	Inari/Ivalo*	0.2	12	1.1.1961–1.7.1992 9 m	

Karman constant (≈0.4), and z_0 is the roughness parameter (m). Values for the roughness parameters were calculated as mean values for every station based on information in the wind atlas of Finland (Tammelin 1991) and are presented in Table 1. After standardization, wind speeds (U) were categorized into three classes: $11\ \mathrm{m\,s^{-1}} \le U < 14\ \mathrm{m\,s^{-1}}$, $14\ \mathrm{m\,s^{-1}} \le U < 17\ \mathrm{m\,s^{-1}}$, and $U \ge 17\ \mathrm{m\,s^{-1}}$. As the 10-minute-average wind speeds represent 1.4–1.7 times as strong wind gusts inland (e.g., Solantie 1983, 1986), the temporal and spatial distribution of the mean wind speeds of 14–17 $\mathrm{m\,s^{-1}}$ also represents wind gusts between 19–29 $\mathrm{m\,s^{-1}}$, and, similarly, the mean wind speeds greater than 17 $\mathrm{m\,s^{-1}}$ represent gusts greater than 30 $\mathrm{m\,s^{-1}}$. For each episode typically related to the passage of a low-pressure area, only the highest wind speed that day was counted.

To analyse how large a share of these high wind speeds had occurred during periods of unfrozen or frozen soil, we had to estimate the soil frost depth. The soil frost depth was calculated only during when the ground was free of snow based on the expression from Venäläinen et al. (2001b):

$$D = a * \sqrt{\mathrm{TS}} - b * \mathrm{TS} \tag{2}$$

where D is the soil frost depth (cm), a and b are coefficients describing the soil properties, and TS is the negative of the sum of the daily average

Table 2. Station information related to precipitation observations. Stations marked by a star are airport weather stations. Observations are made at 06 UTC and 18 UTC if not mentioned otherwise. Lack of data took mainly place in April 1986.

Station	Name	Observations at 06 UTC only	Lack of data
301	Helsinki-Vantaa*		
501	Kotka-Rankki		
1001	Pori*	1.1.2000–	April 1986
1101	Turku*		
1201	Jokioinen obs.		
1501	Utti*		
2101	Kankaanpää		
2401	Jyväskylä*		
3003	Mustasaari		
3201	Kauhava*		
3601	Kuopio*	26.10.2000–	
3801	Joensuu*	1.1.1999–	April 1986
4601	Kajaani*	6.4.2000–	April 1986
5401	Oulu*	1.2.2000–	
6801	Kuusamo*	14.9.2000–	
7401	Rovaniemi*	1.12.1999–	
7501	Sodankylä obs.		April 1986
8201	Muonio		Nov, Dec 1982, Jan 1983
9601	Inari/Ivalo*	5.4.2000–	

temperature T_{daily} (°C) from 1 October to when the frost sum accumulation ends in the spring:

$$\text{TS} = -\sum_{i=\text{1st of October}}^{\text{beginning of spring}} T_{\text{daily}}(t) \tag{3}$$

TS accounts for freezing and melting in the soil, leading to changes in snow frost depth. The largest value for the sum of the cumulative daily temperature was limited to 10 °C to avoid unrealistic values. In this study, $a = 4.42$ and $b = -0.02$, which are the mean values for Finland based on model verification (Venäläinen et al. 2000). The frost depth was classified into the following classes: 1) 0–20 cm, 2) 20–40 cm, 3) 40–60 cm and 4) above 60 cm. Classes 1–4 were used when estimating the impact of climatic change on the windthrow risk of trees (Peltola et al. 1999a). Especially classes 1 and 2 are important for the anchorage of trees in coniferous forest.

2.3 Calculation of the Snow Loads

Previous studies considered the snow load due to single snowfall episodes (e.g., Solantie 1994, Päätalo 2000). In this study, we consider the snow load dynamically, decreasing in response to melting and wind removal and increasing in response to new precipitation with temperature below 2.3 °C therefore besides snow, wet snow, freezing rain or drizzle, even drizzle and rain are included. The expressions for the changing snow load (every 3 h, kg m^{-2}) is developed based on Peltola et al. (1999a,b).

To calculate the loss of snow load by melting (%), we assume that melting starts when the 2-m air temperature T is higher than 0 °C, and, when the temperature is 2.3 °C and above, all the snow will drop off in the next 3 h. This expression for the effect of air temperature on snow load is plotted in Fig. 5a and is as follows:

$$\begin{aligned}\text{Snow loss } (T) &= 11.502\, T^{2.6361}, \text{ when } T \geq 0 \text{ °C}, \\ &= 100, \text{ when } T > 2.3 \text{ °C, and} \\ &= 0, \text{ when } T \leq 0 \text{ °C}\end{aligned} \tag{4}$$

To calculate the loss of snow load by wind removal (%), we assume that when the 10-m wind speed U increases to 10 m s^{-1}, 20% of the snow will fall from the tree (stem and branches)

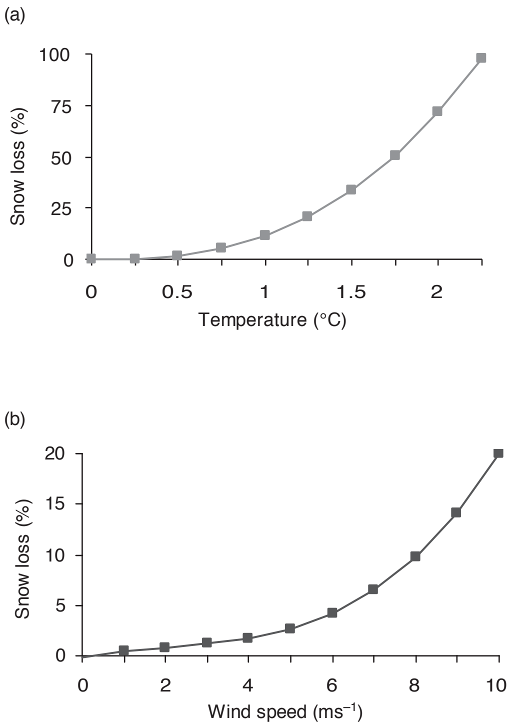


Fig. 5. a) The influence of air temperature on snow loss from trees during three hours, b) influence of wind on snow loss from trees during three hours.

during the next 3 h. This expression for the effect of wind speed on snow load is plotted in Fig. 5b and is as follows:

$$\text{Snow loss } (U) = 0.0338\, U^3 - 0.217\, U^2 + 0.8065\, U \quad (5)$$

To calculate the increase in snow load by precipitation, precipitation measured in mm per 3 h at each station was converted to mass per unit area (kg m^{-2}) for Eq. (6). Based on Eqs. 4 and 5 and measurements of precipitation (prec) in liquid water, the snow load (kg m^{-2}) is calculated for each station every 3 h:

$$\text{Snow load}_n = \text{prec}_n + \text{snow load}_{n-1} \left[1 - (\text{snow loss}_n\,(U) + \text{snow loss}_n\,(T))/100\right] \quad (6)$$

Both rain and snow were included in Eq. (6) because in temperatures 0…+2.2 °C the form of precipitation can vary between snow, wet snow and rain (even including freezing rain and drizzle). The wetter the snow becomes the heavier the load gets. We, however, limited the loading caused by wet snow or rain to below 2.3 °C as expressed in Eq. 4. In some studies the limit is 0.6 °C or 1 °C depending on the method used.

2.4 Use of the Kriging Interpolation Method to Define the Spatial Distribution of the Studied Parameters

To create analyses of the parameters during 1961–2000, the Kriging interpolation method is used. This method follows the theory by Ripley (1981) and the climatological applications to forestry by Henttonen (1991). At FMI, Kriging is routinely used for creating gridded spatial analyses of meteorological and climatological variables from point values (e.g., Venäläinen and Heikinheimo 1997, 2002, Venäläinen et al. 2005).

Kriging works in the following manner. If Z is a meteorological variable having a known value $Z(x_0)$ at a weather station location x_0, the aim is to estimate the value Z at any arbitrary location x (in our case, on a 10 km × 10 km grid covering Finland). In Kriging, the parameter Z at position x is assumed to be a sum of the two components: a slowly-varying *drift* (also called the *trend*) $M(x)$ and a residual referred as the *fluctuation* $e(x)$, so that $Z(x) = M(x) + e(x)$. Both $M(x)$ and $e(x)$ are unknown initially, and the drift $M(x)$ describes the large-scale features of the variable to be interpolated. $M(x)$ is composed of a polynomial of physically meaningful variables such as the geographical location (x,y), elevation above sea level (h), and the percentage coverage of lakes (l) and sea (s). The selection of these variables is dependent on their expected influence on the variable to be interpolated. The functional term of the drift used here is as shown in Eq. 7:

$$M(x,y,h,l,s) = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5xy + a_6h + a_7s + a_8l \quad (7)$$

The coefficients $a_0 \ldots a_8$ were obtained using a least-squares fit method of the observed values of the 19 stations. The fluctuation $e(x)$ is a spatial stochastic process around the M surface with a zero mean. In case the process is isotropic, the spatial covariance between variables at two points depends only on the distance between the two points. The covariance function was obtained by fitting Whittle's correlation function (Ripley 1981) into the residuals $Z(x)-M(x)$. The parameters defining the form of Whittle's covariance were adjusted iteratively by minimizing the error between the interpolated and measured values.

For a given 10 km × 10 km grid square, l and s were calculated as the percentage of lake or sea cover in that grid square. For the observing stations, the percentage of lake or sea is taken as the corresponding value of the grid square inside which the station is situated. When Vajda and Venäläinen (2003) examined the same software for the interpolation of climate in northern Finland using a 1 km × 1 km grid, they found that the geographical position had a significant influence on the regional climate in Lapland. The effect of lakes and sea was secondary. However, we drew the isolines in the maps using relatively coarse intervals because, based on only 19 stations, albeit distributed relatively evenly over the whole country, the small-scale spatial features could not be described in great detail. For the same reason, the trend surface cannot tilt to any direction. Furthermore, as the stations are located at different elevations and in locations with different amount of sea and lake influence all these factors are taken into account. Traditionally, the maps were made manually based on a climatologist's subjective professional skills. Compared to the traditional method used mostly in case studies, the maps made in this work over long time series of data are at least as valuable as any subjective spatial analysis for a single case.

3 Results

3.1 Spatial and Temporal Patterns of Strong Winds

The number of strong-wind cases is high near the coast, close to the lakes, and at higher elevations (Fig. 6a). Inland, the distribution of the 10-minute-average wind speeds in the category of 14–17 m s^{-1} is rather uniform, approximately

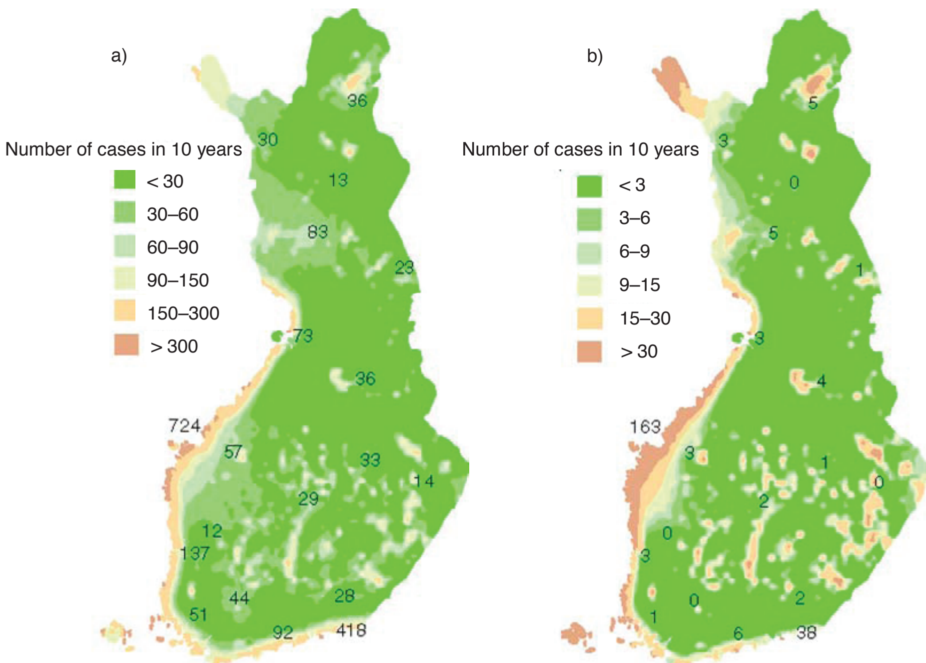


Fig. 6. On the left (a) the spatial distribution of wind speeds ≥ 11 m s^{-1} and on the right (b) the spatial distribution of wind speeds 14–17 m s^{-1}.

Table 3. Statistics of the amounts of observed cases of 10 minute mean wind speeds 1961–2000. Categories are 14–17 $m\,s^{-1}$ and above 17 $m\,s^{-1}$. Shoreline stations measuring wind at sea are marked with gray shading. Averages for all stations, inland stations and shoreline stations are marked on the last three rows.

Station	Cases 14–16 $m\,s^{-1}$	Cases ≥17 $m\,s^{-1}$
Helsinki-Vantaa	25	0
Kotka-Rankki	152	33
Pori	10	0
Turku	2	0
Jokioinen	0	0
Utti	8	0
Kankaanpää	1	0
Jyväskylä	11	1
Mustasaari	651	328
Kauhava	12	1
Kuopio	3	0
Joensuu	0	0
Kajaani	14	0
Oulu	12	1
Kuusamo	3	0
Rovaniemi	21	2
Sodankylä	0	0
Muonio	13	0
Inari/Ivalo	20	0
Station average	50.4	19.3
Inland stations average	9.1	0.3
Shoreline stations average	402	181

two times in ten years (Fig. 6b; Table 3).

According to the 19 stations used in the study, the amount of the higher wind-speed cases have neither increased nor decreased over time (Fig. 7a). But, the temporal variability has been large (Fig. 7b). For instance, in the 1960s there were fewer cases of wind speeds exceeding 11 $m\,s^{-1}$ than in the 1970s and 1980s. The beginning of the 1990s had an above average number of strong wind events, but towards the millennium the number of events with wind speeds exceeding 11 $m\,s^{-1}$ decreased to a relatively low level (Fig. 7b). On the other hand, compared to the mean value of observed cases of wind speeds above 14 $m\,s^{-1}$, 1965–1985 had most of the strongest wind cases during 1961–2000.

3.2 Simultaneous Occurrence of Frozen Soil and Strong Winds

Essential to the wind-induced risks in forests is whether the soil is frozen or not simultaneously with strong winds. Strong wind speeds were most common in soil frost depth categories 0–20 cm and above 60 cm (Fig. 8). In southern Finland and the western coast, most of the strong winds have taken place in the soil frost depth category 0–20 cm. In the northern parts of Finland strong winds have appeared especially when the soil frost depth has exceeded 60 cm. This bipolar distribution is due to the fact that 0–20 cm and above 60 cm categories are the most common frost depths. In northern Finland the soil frost depth increases rapidly from October on reaching 40–60 cm already in November but the period of unfrozen or just slightly frozen soil lasts rather long in the more southern and especially coastal areas. According to the distribution of the monthly soil frost depth, when wind speed has been at least 11 $m\,s^{-1}$ (Fig. 9), the wind induced risk for damage has been greatest in October–December.

3.3 Comparison of the Used Snow Load Calculation Method to Winter 1993–1994 in Lapland

To show that the equations developed and used in this work are able to give reasonable results, we compared the analysed snow loads to weather conditions during winter 1993–1994 that, according to the forest inventory (Metsätilastollinen vuosikirja 1999), caused a lot of snow damage in Lapland. In January 1994 in Lapland, the mean monthly temperature was 1–2 °C lower than the long-term average of 1960–1990 (*normal*) and the precipitation amounts were 125–200% of normal. If the new method was to give reasonable results, we should expect to see large snow-load values in Lapland in January 1994. Indeed, in Sodankylä (Fig. 10a), the snow loads were usually above 30 $kg\,m^{-2}$ from 10 December 1993 to 4 February 1994, and the heaviest snow loads (above 50 $kg\,m^{-2}$) happened in January. In January, the temperature varied between 0° and –35 °C, and the winds were mostly less than 5 $m\,s^{-1}$. Therefore, the snow loads could increase rather constantly

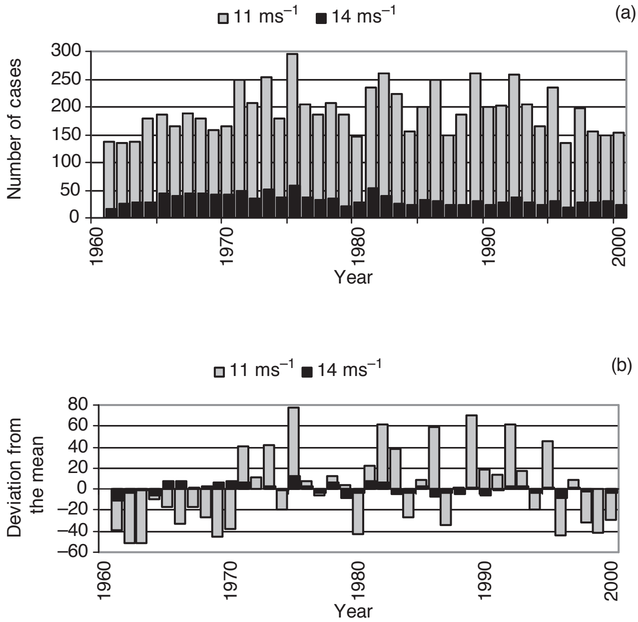


Fig. 7. a) The amount of wind cases above 11 $m s^{-1}$ and 14 $m s^{-1}$ in Finland in 1961–2000 and b) the yearly deviation from the mean for same categories. For example in 1994, 1996 and 1998–2000 the number of cases with wind speeds above 11 $m s^{-1}$ and 14 $m s^{-1}$ were clearly below average.

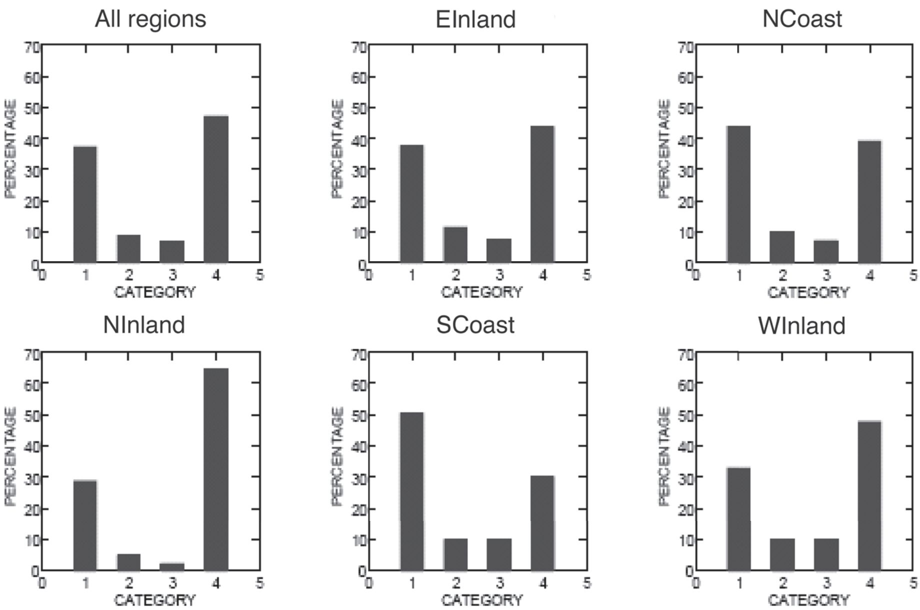


Fig. 8. The percentages of frost categories 1 (0–20 cm), 2 (20–40 cm), 3 (40–60 cm) and 4 (above 60 cm) when wind speed exceeds 11 $m s^{-1}$. Results are presented for Finland (all regions), and the coastal and inland smaller areas: EInland = eastern inland, NCoast = Northern coastal region, NInland = Northern inland, SCoast = southern coastal reagion and WInland = western inland.

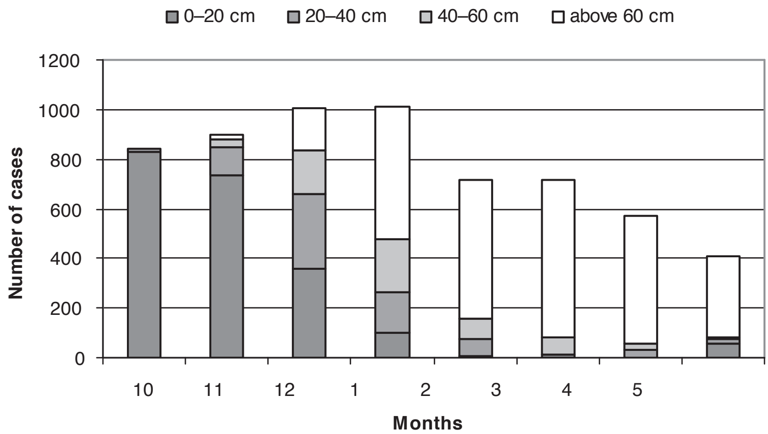
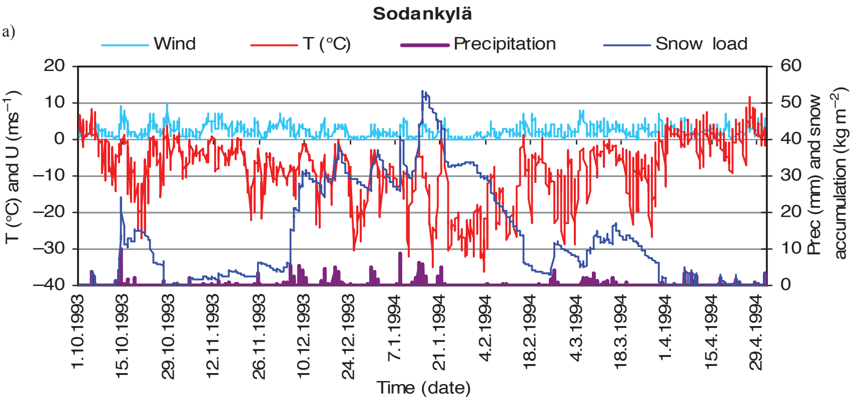


Fig. 9. Monthly distribution of soil frost depth classes 0–20 cm, 20–40 cm, 40–60 cm and above 60 cm when the 10 minute mean wind speed has exceeded 11 m s^{-1}.

a)



b)

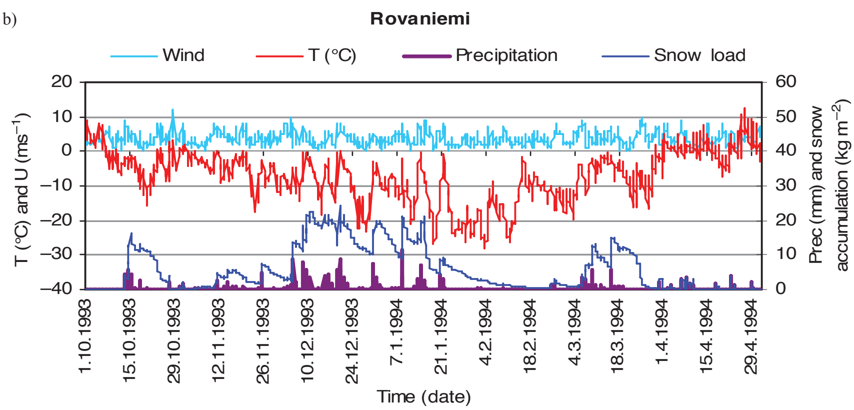


Fig. 10. Examples on how the Eq. 6 works in reality. In figures a) Sodankylä and b) Rovaniemi the data is from 1.10.1993–1.5.1994. At these stations the heavy snow loads were expected to have taken place in January according to the monthly weather statistics of January 1994. Snow loads were very high (30–50 kg m^{-2}) in Sodankylä for nearly two months.

with snowfall because the loss of snow by wind or temperature was small. In Rovaniemi (Fig. 10b), snow loads stayed mainly at 20 $kg\,m^{-2}$ level, in part because the wind was generally stronger (5–10 $m\,s^{-1}$) and snow loss was larger. Comparing Rovaniemi to Sodankylä that received similar amounts of precipitation as Rovaniemi during January 1994, the importance of higher wind speeds to limiting snow load is clear.

3.4 Spatial and Temporal Patterns of Heavy Snow Loads

Based on the model analyses of snow accumulation, the differences in the spatial distribution of snow loads above 20 $kg\,m^{-2}$ are large (Fig. 11). The risk of significant snow loads is largest in the northern and eastern parts of Finland, which is in good agreement with the climatic conditions. In the eastern and northern parts of Finland, the mean annual maximum snow depth is 60–100 cm, whereas in southern and central Finland, average snow depth is only 30–40 cm (Fig. 2). The number of days when trees have been exposed to at least 20 $kg\,m^{-2}$ snow loads in the north and in the east has varied between 40 and 160 days per decade. In southern Finland, the exposure is of the order one to three days per year and in the western part once to five times in a decade. On the shoreline, the risk exists only 0.3–1 times in a decade.

Based on the station location, the risk of snow loads above 30 $kg\,m^{-2}$ has varied from 2 to 28 days per decade. In southern Finland, based on Table 4, the risk has been largest close to Turku (station 1101), Utti (station 1501), Kankaanpää (station 1201) and Jyväskylä (station 2401) with 40–100 risk days per decade. In the northern part the risk has been even higher: approximately i.e., 110–270 days per decade. The highest snow load observed in this work was 64 $kg\,m^{-2}$ in Ivalo.

The temporal variability in the occurrence of the heaviest snow loads according to the analyses is large. A time series from Kuusamo (Fig. 12) 1961–2000 reveals that the maximum annual snow loads varied mostly between 15 and 25 $kg\,m^{-2}$ in the 1960s and 1970s. However, in 1968, the peak value was nearly 40 $kg\,m^{-2}$. Similar snow loads have happened otherwise only in 1993, 1994 and 1999. In the 1980s the maximum annual snow loads varied between 25 and 35 $kg\,m^{-2}$ and in the 1990s between 20 and 45 $kg\,m^{-2}$.

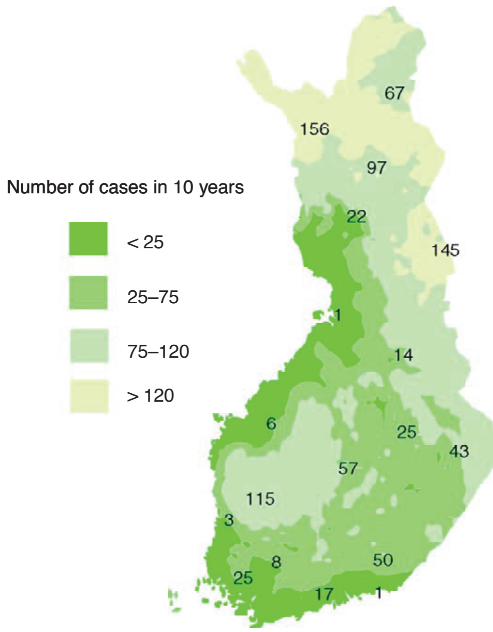


Fig. 11. Spatial distribution of snow loads above 20 $kg\,m^{-2}$.

The risk for heavier snow loads has been increasing during 1961–2000 (Fig. 13). The risk of above 20 $kg\,m^{-2}$ snow loads was on average 50–60 days per year in the 1960s and 1970s considering the whole country, in the 1980s somewhat greater being 80–90 days per year. In the 1990s the risk on snow loads above 20 $kg\,m^{-2}$ was highest, being almost 150 days per year. The increase in the snow loads in 40 years is significant (Fig. 13) and cannot be explained by changes that happened in the instruments measuring precipitation in the beginning of 1980s.

Table 4. Number of days when the snow accumulation values according to the model results has exceeded 30 kg m^{-2}. Yearly sum of all cases according to the stations is marked on the right and the 40 year sums of each station are marked under the table. Link between station numbers and station names is given in Table 2. Stations having no values exceeding 30 kg m^{-2} have been omitted from the table.

Station/Year	301	1101	1501	2101	2401	3201	3601	3801	4601	6801	7501	8201	9601	Σ
1961	5		3											8
1962														
1963														
1964														
1965	2		2								2			6
1966				5	2							8		15
1967													5	5
1968		1		1	5					3				10
1969				2	9									11
1970					11									11
1971														
1972														
1973														
1974				3										3
1975														
1976														
1977				6								3		9
1978												2		2
1979				3										3
1980										4				4
1981										1				1
1982			6			5								11
1983								5		1				6
1984		2												2
1985												1		1
1986							9			2				11
1987														
1988														
1989		1								1				2
1990				1	1					1				3
1991			1	3						1	9	10	3	27
1992				14	10									24
1993										14	1	11	6	32
1994										29	15	46	16	106
1995		2	2							2			8	14
1996											1	7	7	15
1997		1												1
1998										2	7	18	39	66
1999									6	11				17
2000											9	2	8	19
Σ	7	7	14	38	38	5	9	5	6	72	44	108	92	445

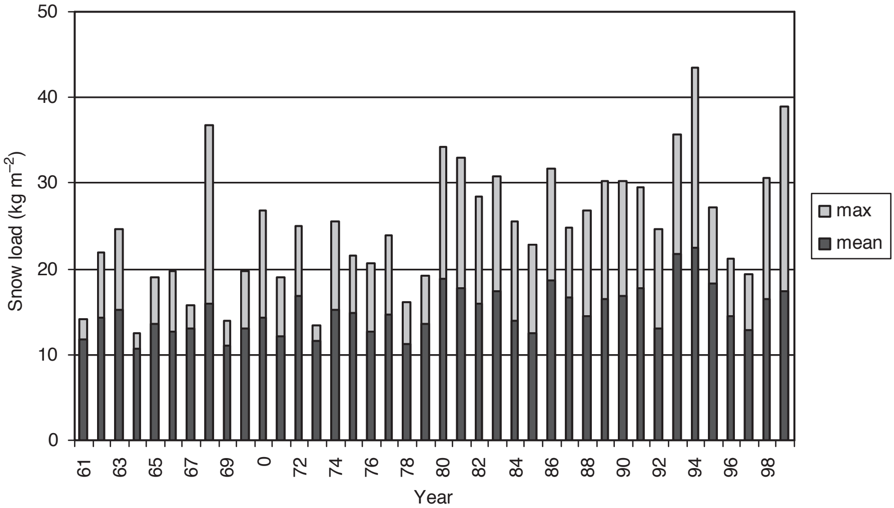


Fig. 12. The yearly mean (black) and maximum (gray) snow loads in Kuusamo during 1961–2000.

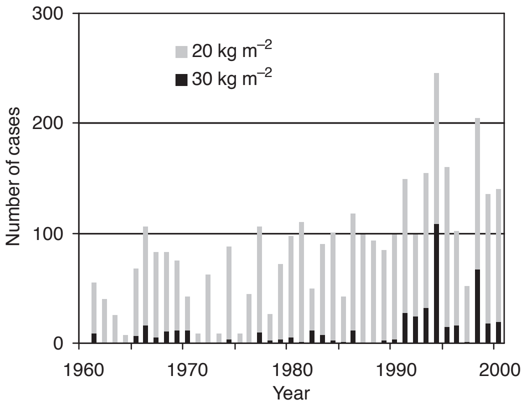


Fig. 13. The temporal variation of snow loads above 20 $kg\,m^{-2}$ (gray) and 30 $kg\,m^{-2}$ (black) during 1961–2000.

4 Discussion

4.1 Evaluation of the Research Methodology

The results presented in this work are based on wind, temperature, and precipitation measurements collected by meteorological observing stations operated by FMI. The need for continuous and homogenous data reduced the number of possible stations for this study because only a minority of FMI's meteorological stations has been functioning the whole period 1961–2000. Thus, we used only 19 stations, most of which were airport weather stations. Although the snowfall and wind speed at airport weather stations are likely not representative of those same measurements in nearby forest, the data from these stations produced the best, most continuous dataset available. Furthermore, the stations happened to be evenly distributed across Finland, providing a good dataset for the spatial analysis. With this small number of stations, however, we cannot claim that the Kriging analysis would be capable of representing many small-scale features. The distribution maps for the wind and snow loads from this study are first of their kind, providing a basis for further research on climate change impacts on wind- and snow-induced risks in the forest.

Table 1 shows that the heights of the wind measurements have varied greatly during 1961–2000. To standardize the height of the wind observation, we applied the logarithmic wind profile to wind data not taken at 10 m above the ground in section 2.2 of this article. However, the logarithmic wind equation is best suited for neutral atmospheric conditions and may not be appropriate when the boundary layer is either stable or unstable (e.g.

Holton 1992, Cp. 5). Because we have concentrated on the stronger surface winds that have been observed between 10–30 meters above the ground, conditions when the near-surface layer is likely to be well mixed, the standardization may not be unreasonable. On the other hand, weaker winds during cold episodes with strong near-surface stability may be overestimated by the logarithmic wind profile. Thus, the decrease in snow load in weak wind cases in the analysis may be too fast compared to reality, leading to snow-load durations being somewhat underestimated.

On the contrary, precipitation measurements have not been adjusted in any way. With strong winds, 30–50% of snowfall may be blown around or over the gauges (e.g., Goodison 1978, Tammelin 1984, Solantie 1985a,b, Sarkanen 1989). If the measurements of precipitation data had been wind corrected, we might have got different results. The net impact of errors in measuring precipitation is complicated to estimate because of competing effects. On the one hand, wind results in an underestimate in measured precipitation amounts inside precipitation gauges. Gauge-based precipitation is probably also underestimated because of snow loading on trees, which will be a function of temperature and snow crystal type. On the other hand, snow loads decrease with higher wind speeds. Perhaps, in cases when the wind blows from one direction, temperature is just slightly below zero and snowfall is abundant, the peak snow loads are underestimated.

The method used for estimating the soil frost depth was originally developed for road-weather applications, when a valid assumption is that the ground is free of snow. In a forest, however, such assumptions are less appropriate. In coniferous forests, however, the snow depth develops more slowly than in the deciduous forest in the fall and in the beginning of winter. So, Eqs. 2 and 3 may not be poor assumptions, even for coniferous forests during October–December. The soil frost depths may even be underestimated for mild winters (Venäläinen et al. 2000). On the other hand, later in the winter and especially in the spring, Eqs. 2 and 3 are likely to slightly overestimate the soil frost depth in forests (Huttunen and Soveri 1993, Solantie 2000, Solantie and Drebs 2001).

4.2 Spatial and Temporal Patterns of Strong Winds and Heavy Snow Loads

In this article, time series of forty years of 10-minute-average wind speed, soil frost depth, and snow loads were constructed to partly explain the wind- and snow-induced damage in Finnish forests. The results of previous studies on wind- and snow-induced damages to Finnish forests (Solantie 1983, 1986, 1994, Peltola et al. 1999, 2000, Päätalo 2000) and on soil frost depth (Venäläinen et al. 2000) were used to guide the development of the snow-load calculations.

According to Fig. 6, most of the strong wind cases near the coasts occurred when the frost depth was less than 20 cm. In eastern and northern Finland, most of the strongest wind events occurred during December–January when the soil frost depth was greater than 60 cm. Thus, the risk of wind damage was considerably smaller inland than near the coast. On the other hand, trees in coastal forests may have adapted to the higher wind speeds (i.e., higher diameter-to-height ratio).

In contrast to the distribution of high wind speeds (Fig. 3), the largest snow loads per square metre of crown area are typically found in the higher-elevation inland areas (Fig. 8). In northern and eastern Lapland, for instance, the exposure is approximately 150 times in a decade. In western Finland, a distinctive local maximum exists in the occurrence of the larger heavy snow cases, which is explained by the steep rise in topography (120 m in 60 km).

4.3 Impacts of the Ongoing Climate Change on Snow- and Wind-Induced Risk to Finnish Forests

In our work, the risk of heavier snow loads increased during 1961–2000. In the 1990s, the risk of snow loads above 20 kg m^{-2} was almost 150 days per year, whereas, in the 1960s and 1970s, the risk was 50–60 days per year. The increasing trend may be to be linked with the warming of the climate. Our findings gain support from the work of Venäläinen et al. (2005), Räisänen and Joelsson (2001), Räisänen et al. (2003), (2004), Ruokolainen (2005) and Ruosteenoja et al. (2005). According to Venäläinen et al. (2005), the climate of Finland has been 0.5 °C warmer in 1991–2000 compared to the mean of 1961–2000. Decembers and Januarys in 1991–2000 have been warmer than the 1961–2000 mean (1.6 °C and 2.4 °C, respectively). The monthly mean precipitation amounts have increased in the 1990s as well, being 13–36% more than the 1961–2000 mean (Venäläinen et al. 2005). According to climate models (Räisänen and Joelsson 2001, Räisänen et al. 2003, 2004, Ruokolainen 2005, Ruosteenoja et al. 2005), warming will result in an increase of winter precipitation and larger daily snowfall amounts (Ruokolainen 2005). Towards the end of the century, however, warming of the climate will already be so large that the risk of snowfall will decrease and winter precipitation will more likely fall as rain. Based on our work and the climate model results, the increasing trend in the snow-induced risk to forest will therefore reach its maximum and start to decline.

Another important aspect besides the warming of the climate and increase in precipitation and humidity (Räisänen et al. 2003) is the weakening of the winds (Fig. 4b) that seems to be the other key to the heavy snow loads in the 1990s. The weakening of the winds in the 1990s cannot be explained by this study nor by the conflicting results of the climate model runs (e.g., Räisänen et al. 2004, Ruosteenoja et al. 2005), but it would be interesting to investigate why the changes in the wind climate in Finland have taken place.

Either way, by including proper risk management of wind- and snow-induced damages into forest planning (related to the timber harvesting objectives set), the risk of wind and snow damage could be reduced. For example, the number of the vulnerable edges for wind damage could be reduced by: i) aggregating clear-cuttings, ii) locating clear-cuttings at the edges of young stands (i.e., tree height < 10 m) or stands with critical wind speeds high enough to indicate lower level of risk of damage and iii) by smoothing the landscape by decreasing the spatial fragmentation of stand height (Zeng et al. 2004, 2007). On the other hand, the importance of any risk management actions depend on the probability of high wind speeds and the occurrence of large snow loading on trees in the region concerned. Therefore, any attempt to develop suitable management practices to reduce the future risks of damage requires spatial information on critical wind and snow values, such as provided by this study. Such results will be crucial in the future when the risks of wind- and snow-induced damage are expected to take place under the changing climate.

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