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Combined Occurrence of Wind, Snow Loading and Soil Frost with Implications for Risks to Forestry in Finland under the Current and Changing Climatic Conditions

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This work focuses on the combined occurrence of wind, snow loading and soil frost with implications for risks to forestry in Finland under the current and changing climatic conditions. For this purpose, we employ meteorological datasets, available for the period of 1971–2009 and global climate model (GCM) simulations for the current climate 1971–2000, and periods 2046–65 and 2081–2100 applying the A1B-climate change scenario. Based on our results, the wind and snow induced risks to Finnish forests are projected to increase in the future although the change in the occurrence of strong winds is small. This is because soil frost depths that support tree anchorage from late autumn to early spring in Finland are projected to nearly disappear in the southern and central parts of the country. Heavy snow loads >30 kg m^{-2} are becoming more common in southern and eastern Finland despite that the average cumulative 5-day snow loads decrease in these areas by 18 to 50%, respectively. As a result of the changes in the combined occurrence of wind, snow loading and soil frost, the risk of climatic conditions making conifers liable to uprooting are projected to increase in southern, central and eastern Finland. In the north, the risk of stem breakage is becoming more pronounced under snow loading >20 kg m^{-2}. Despite some uncertainties related to this work, we assume that the findings can serve as valuable support for the risk assessment of wind and snow induced damages to Finnish forests and for forestry, in general.

Keywords A1B-scenario, climate change, snow loads, soil frost, stem breakage, uprooting, wind
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1 Introduction

Storms and strong winds cause significant damages to forests in northern and central Europe. For example, in 1990 and 1999 a total of 100 and 175 Mm^3 of timber blew down in winter storms "Lothar" and "Vivian" that affected Europe in wide areas (e.g. Ulbrich et al. 2001, Brüdl and Rickli 2002, Dobbertin 2002, Schönenberger 2002). In the "Gudrun" storm, in January 2005, approximately 70 Mm^3 of timber was damaged in Sweden (Alexandersson 2005, Bengtsson and Nilsson 2007), while in the "Kyrill" storm in January 2007 about 45 Mm^3 was damaged in Central Europe (e.g. Fink et al. 2009). As a comparison, in Finland a total of 7 million m^3 of timber was damaged in November 2001 in two separate storms ("Pyry" and "Janika"), while in 2010 (July–August) a total of 8 million m^3 of timber was damaged in four severe summer storms.

The economic impact of damages caused by storms and strong winds is particularly severe in managed forests due to the reduction in the yield of recoverable timber and value of harvested timber and increased costs of harvesting. Furthermore, broken and uprooted trees left in the forest can lead to detrimental insect attacks on the remaining trees because the amount of available breeding material increases in such forests. In boreal forests, strong winds with or without heavy snow loading on trees cause uprooting, especially during unfrozen soil conditions, whereas stem breakage occurs typically during frozen soil conditions under heavy snow loading, as well as in summer thunderstorms (e.g. Laiho 1987, Solantie 1994, Peltola et al. 1999, Gregow et al. 2008a,b). The susceptibility of tree stands to damage is also dependent on the topography, site conditions and tree and stand characteristics, the latter ones being affected by forest management (e.g. Laiho 1987, Lohmander and Helles 1987, Päätalo et al. 1999, Peltola et al. 1999, Peltola et al. 2010).

Several studies have shown that wind damage in Finland may occur with relatively low mean wind speeds (10 min mean), with a range of 11–17 m s^{-1}, or even with a range of 9–13 m s^{-1} if related to additional snow loading (e.g. Solantie 1983, 1986, Laiho 1987, Talkkari et al. 2000, Pellikka and Järvenpää 2003, Gregow et al. 2008a,b). These wind speeds are clearly lower than those winds causing damage in other parts of Europe, mainly due to the milder wind climate in Finnish conditions (i.e. forests have not acclimated to strong winds). Extensive forest damage is also primarily caused by strong wind gusts. Such strong non-convective wind gusts are typically associated with extra-tropical storms, and occur in the vicinity of their cold fronts (e.g. Fink et al. 2009). As pointed out by Knox et al. (2011), other mechanisms are possible, including the occurrence of sting jets (e.g. Baker 2009) or low level jets (Gregow et al. 2008a). The wind gusts may exceed mean winds (discussed above) by more than 100% (e.g. Brasseur 2001). According to Usbeck et al. (2010), the occurrence of gust wind speeds exceeding 40 m s^{-1} have increased in recent winters in Europe.

The occurrence of wind induced damage has so far been most severe in the southern and western parts of Finland, which represent the windiest regions, if excluding the high altitude locations in the north (Puranen 2006, Gregow et al. 2008b). As a comparison, the risk of low to moderate snow damage (20 to 40 kg snow per m^2) has occurred, on average, every fifth year in southern Finland, every third year in eastern and northern Finland and once or twice in 20 years in western and central Finland (Solantie 1994). Snow-induced damage is most likely in Finnish conditions under circumstances in which the air temperature is between –3° and +0.6 °C and wind speed is relatively low (e.g. Solantie 1983, 1986, 1994). According to Päätalo (2000), coniferous trees can break or uproot in unmanaged stands (i.e. being typically quite slender trees) already with 10–25 kg m^{-2} snow loads, when in managed stands snow loads of 54–60 kg m^{-2} and 17–53 kg m^{-2} are needed for stem breakage and uprooting in Finnish conditions, respectively.

In Finland, the mean temperature in winter is projected to increase until 2070–2099 by 4–7 °C, while the amount of precipitation is projected to increase by 20–30% in the case of the A1B-scenario (Jylhä et al. 2009). Especially heavy winter precipitation is projected to occur more often. Correspondingly, according to Räisänen (2008), the snow fall season is projected to become shorter based on simulations using 20 global climate models (GCMs) and assuming the SRES A1B-scenario (Nakicenovic et al. 2000). As a result of climate warming, the soil frost occurrence and duration is also expected to decrease. For example, Venäläinen et al. (2001b) suggested that the annual maximum soil frost depths in Finland will decrease, on average, by 50% by 2100. According to Peltola et al. (1999), the duration of soil frost will decrease in southern Finland from 4–5 months to 2–3 months, which is also in line with the most recent work by Kellomäki et al. (2010).

Due to climate change, the risk to uprooting of trees is expected to increase in Finland. This is firstly because the additional support given by soil frost for the anchorage of trees is projected to decrease during the windiest period, i.e. from late autumn to early spring (Peltola et al. 1999, Venäläinen et al. 2001a,b, Kellomäki et al. 2010). Additionally, the cyclone tracks are projected to shift (Bengtsson et al. 2006, 2009, Leckebusch et al. 2006, Ulbrich et al. 2008). For example, Pinto et al. (2009) have suggested an increase of rapidly developing cyclones especially for storms moving from the North Sea into the Baltic Sea. Fortunately, in Finland the daily mean and maximum wind speeds are projected to change only by a few percent points (Gregow et al. 2009).

On the other hand, if precipitation increases simultaneously with the occurrence of a temperature range of –3° to +0.6 °C, heavier snow loads may occur due to slightly warmer climate, wetter snow and increasing precipitation (Carter et al. 2005, Ruokolainen 2005). This can enhance the risk of snow-induced damage in the near future (Kilpeläinen et al. 2010). Varying wind speeds, snow load and soil frost conditions cause risks to forests also in interaction. Therefore, information regarding the risks of such conditions is crucial in order to properly assess their implications for forests and forestry. This is also important because the growing stock of forests will increase in a changing climate as a result of the enhancement in growth (e.g., Kilpeläinen et al. 2010, Peltola et al. 2010), which may also increase the risks to forests.

This work aimed at studying the combined occurrence of wind, snow loading and soil frost with implications for risks to forestry in Finland under the current and changing climatic conditions. More specifically, we studied the frequency distributions of different wind speeds and simulated geostrophic wind speeds which can be used as rough estimates for surface gust wind speeds. Furthermore, we studied the combined occurrence of different 1) wind speeds and snow loads, 2) wind and soil frost depths, 3) snow loads and soil frost depths, and finally 4) wind speeds, snow loads and soil frost depths at the same time. This was done in order to estimate how the climatic conditions that cause risk to uprooting or stem breakage of trees are projected to change in the future. For this purpose, we used the most recent meteorological datasets available from the Finnish Meteorological Institute for the current climate (1971–2009). Climate change effect was studied by utilizing the global climate models (GCM). The control runs considered a 30-year period from the end of the 20th century and the future runs focused on two 20-year periods (2046–65 and 2081–2100) assuming the A1B-climate change scenario (Nakicenovic et al. 2000). The results of this work are expected to serve as valuable support for the risk assessment of wind and snow induced damage (i.e. in terms of uprooting and stem breakage) to Finnish forests, and for forestry in general.

2 Material and Methods

2.1 Outlines for the Data Analyses under the Current and Changing Climate

In this work, we studied the occurrence of wind, snow loading and soil frost based on the observed climate of 1971–2009 and the global climate model (GCM) runs concerning the current climate of 1971–2000 (the model CSIRO had data from 1960–1980, 1990–2000) and the future periods of 2046–65 and 2081–2100 when the A1B-climate change scenario (Nakicenovic et al. 2000) was assumed. For making estimates of the projected climate change we used the monthly mean temperature and precipitation of the 19 GCM simulations that were also investigated by Jylhä et al. (2009) and the daily temperature and MSLP (mean sea level pressure) of ten GCMs (Table 1).

Table 1. The model ID, the institute responsible for the model and the resolution and/or grid spacing is shown for the 10 GCMs that were employed for calculation of wind by using the daily 24-hour MSLP and temperature. The changes in the monthly temperature and precipitation were analysed using in total of 19 GCMs (employing also CGCM3.1-T47, GFDL-CM2.0, GISS-ER, INMCM3-CM3.0, MIROC3-MEDRES, MIUB-ECHO-G, NCAR-PCM1, UKMO-HadCM3 and UKMO-HadGEM1, see details for models from IPCC, 2007, Table 8.1).

Model ID	Institute	Resolution
BCCR-BCM2.0	Bjerknes Centre for Climate Research	T63(1.9°×1.9°)
CSIRO-Mk3.0	CSIRO Atmospheric Research Australia	T63(1.9°×1.9°)
CGCM3.1(T63)	Canadian Centre for Climate Modelling and Analysis	T63(1.9°×1.9°)
CNRM-CM3	Météo-France	T63(1.9°×1.9°)
ECHAM5/MPI.OM	Max Planck Institute for Meteorology	T63(1.9°×1.9°)
GFDL-CM2.1	National Oceanic and Atmospheric Administration	2.0°×2.5°
IPSL-CM4	Pierre Laplace Institute	2.5°×3.75°
MIROC3.2(hires)	Japan Center for Climate System Research	T106(1.1°×1.1°)
MRI-CGCM2.3.2	Japan Meteorological Research Institute	T42(2.8°×2.8°)
NCAR-CCSM3	The National Center for Atmospheric Research	T85(1.4°×1.4°)

Table 2. The locations of the used grid points and observation stations of Finnish Meteorological Institute (FMI) are given with latitude (°N) and longitude (°E).

Location	GCM grid point	LARS-WG grid point	FMI station
Helsinki	60.0 N; 25.0 E	60.375 N; 24.875 E	60.372 N; 24.960 E
Joensuu	62.5 N; 30.0 E	62.625 N; 29.625 E	62.660 N; 29.615 E
Jyväskylä	62.5 N; 25.0 E	62.375 N; 25.625 E	62.402 N; 25.679 E
Kajaani			64.281 N; 27.679 E
Kauhava			63.120 N; 23.047 E
Rovaniemi	65.0 N; 25.0 E	66.625 N; 25.875 E	66.558 N; 25.835 E
Sodankylä			67.366 N; 26.633 E

Under the current climate of 1971–2000 (CU), all the wind, snow loading and soil frost calculations were done for seven locations (see Table 2), whereas under the changing climate (CC) they were done only for four locations (using the closest point of the observation stations in the 0.25°×0.25° grid). The variables investigated under the CU were: 10 min daily mean and maximum wind speed (m s^{-1}) at 10 meter height (especially in September–May), directional distribution of wind speeds above 8 m s^{-1} (wind roses), cumulative snow loads (kg m^{-2}) and soil frost (cm) of the snow free (road) ground. The return levels of 2, 5 and 10 years for the occurrence of the annual maximum observed 10 min mean wind speeds, geostrophic wind speeds as well as cumulative snow loads were also calculated for each location. Under the CC the corresponding variables were analysed excluding, however, the directional distribution of wind speeds and the return levels.

In this work, we studied, in detail, the occurrence of wind speeds and observation based modeled cumulative snow loads and GCM-based modeled 5-day snow loadings in September–May in different wind speed (0–3, 4–7, 8–10 and ≥11 m s^{-1}) and snow load (10–20 kg m^{-2}, 20.1–30 kg m^{-2} (later called as 20–30 kg m^{-2}) and >30 kg m^{-2}) classes, regardless of climate. Furthermore, the snow free soil frost depth was analyzed using the following soil frost limits: 1) <20 cm, 2) 20–40 cm, 3) 41–60 cm and 4) >60 cm, which correspond to about double the actual depths of forest soils based on previous soil frost measurements done by the Finnish Environmental Institute during winter 2008–2009.

The change in the climatic conditions making trees vulnerable to uprooting and stem breakage

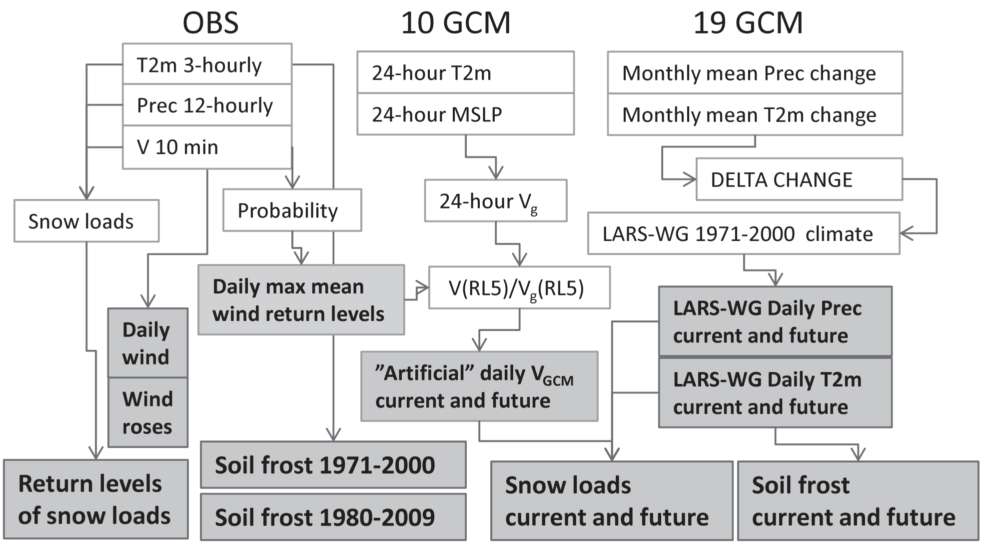

Fig. 1. Schematics of the main data and methods flow in this work. T2m is the air temperature (°C) at 2 meter height, MSLP is the mean sea level pressure (hPa), Prec is the precipitation (mm), V is the observed 10-min mean wind speed (m s^{-1}), V_g is the geostrophic wind speed, and daily V_{GCM} is the average "artificial" surface wind speed of 10 GCMs. The grey boxes indicate the main results that were obtained in this work.

was evaluated based on the analyses of the concurrent occurrence of various soil frost depths together with a range of wind speed and/or snow load classes under the CU and CC. In this context, we analyzed in the details especially the changes in the occurrence of snow loads >20 kg m^{-2} and the concurrent occurrence of daily average GCM wind speeds >6 m s^{-1} when snow free soil frost depth was ≤60 cm (indicating potential risk for uprooting if actual forest soil frost is ≤30 cm) and above 60 cm (potential risk for stem breakage if the actual forest soil frost depth is >30 cm). The main data flow in this work and how the different aspects are combined in the data analyses is schematically described in Fig. 1.

2.2 Datasets Used for Analyses under the Current Climate and Changing Climate

Datasets Used for Wind, Snow Loading and Soil Frost Analyses under the CU

The wind observations used in this work for the current climate of 1971–2000 were taken from a height of 10 m for following stations: Helsinki, Jyväskylä, Joensuu, Kauhava, Kajaani. In Rovaniemi the wind anemometer was placed at 11 m height in June 1987 and in Sodankylä all the measurements were made at a height of 22 m. Therefore, the 10 minute mean wind speeds measured every 3 hours at different heights were standardized to a uniform 10 meter height based on the use of the logarithmic wind profile (e.g. Holton 1992, p. 132):

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

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 Karman constant (≈0.4), and z_0 is the roughness parameter (m). In Joensuu, there were some missing wind observations for 1996/1997 and 1998 (see Puranen 2006 and Gregow et al. 2008b for further details).Values for the roughness parameters were calculated as mean values for each location based on information from the wind atlas of Finland (Tammelin 1991).

Observed wind speeds are typically available as 10 minute mean wind speeds but the only timely resolution available for GCM simulated geostrophic wind speeds for the 20- and 30-year periods is the daily average. Even though it is the strong wind gusts that especially enhance the damage, the geostrophic wind is considered here, as it is more systematically calculated from the GCM data than wind gusts. In order to compare the daily wind speeds to 10 min mean wind speeds and vice versa, we averaged the observed 3-hourly 10 min mean wind speeds to daily wind speeds. Additionally, we used the highest observed 3-hourly value to represent the highest daily mean wind speed. The distributions of these two sets of daily wind speeds were studied in more detail (see Section 3.1). We also plotted wind roses for wind speeds ≥8 m s^{-1} for the CU by using 10 minute wind speed and the available direction data (mainly from a height of 10 m) for 1971–2000 from September to May by employing the software WRPlot View offered in the internet as a freeware by Lakes Environmental.

The data that was used for calculating the return periods of the observation based cumulative snow loads under the CU was the 10 minute average wind speed and 2-meter air temperature (both measured every 3 h), and 12 h liquid water equivalent of precipitation for the period 1971–2000. The observation based snow loads were calculated as in Gregow et al. 2008b, but the GCM-based snow loads (for the CU and CC) were calculated on a daily scale according to Section 2.5. The soil frost was calculated both for 1971–2000 and 2001–2009 to analyze the change in soil frost from 1971–2000 to 1980–2009. The measured temperature datasets used in this work covered two periods, one for 1971–2000 (for details see Gregow et al. 2008b) and another one for 2001–2009 (data obtained from the Finnish Meteorological Institute).

Datasets Used for Wind, Snow Loading and Soil Frost Analyses under the CC

In this work, we used data that was downloaded from the Coupled Model Intergovernmental Project 3 (CMIP3) archive (Meehl et al. 2007). More specifically, we used the GCM simulated data for 24-hour mean sea level pressure (MSLP), 24-hour mean and monthly mean temperature and monthly mean precipitation of the control climate 1971–2000 and the future periods of 2046–65 and 2081–2100 assuming the A1B scenario. The grid points chosen for this work represented four locations: Helsinki, Jyväskylä, Joensuu and Rovaniemi (i.e. for the closest point in the 0.25°×0.25° grid). The ten GCMs (see Table 1) used for estimating the changes in the 24-hour geostrophic wind speeds in this work represent separate meteorological institutes and have spatial resolution of about 300 km (T42) or higher and form a subset of the 23 models used in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report of 2007. The analyses of the changes in the monthly temperature and precipitation for periods of 2046–65 and 2081–2100 compared to CU were based on simulation data of 19 GCMs (for more details, see Jylhä et al. 2009, the IPCC 4th Assessment Report in 2007). We used different number of GCM simulations for estimating the changes in the 24-hour geostrophic wind speeds compared to 24-hour mean sea level pressure (MSLP), 24-hour mean and monthly mean temperature and monthly mean precipitation, because these datasets were expected to provide the most representative results based on current understanding, and especially when the daily average results were considered. This option may, however, imply some uncertainties for the results.

The future projections needed for the daily temperature and precipitation were created from the historical data (1971–2000) based on the adopted changes in the monthly mean temperature and precipitation at grid resolution 0.25°×0.25° over the whole Finland by Jylhä et al. (2009). The projected increases of monthly mean temperatures were first added by using the so-called delta-change method (e.g. Agresti 2002) to the observed monthly means for current climate. For precipitation, the observed corresponding means were multiplied by the projected relative changes. Then the stochastic weather generator LARS-WG (Racsko et al. 1991, Semenov and Barrow 2002, Semenov 2007, Semenov and Sratonovitch 2010) was used to produce simulated daily temperature and precipitation for current and changing climate for the periods of 1971–2000, 2046–2065 and 2081–2100, respectively.

The time series needed for the 24-hour mean geostrophic wind speeds for CU and CC peri-

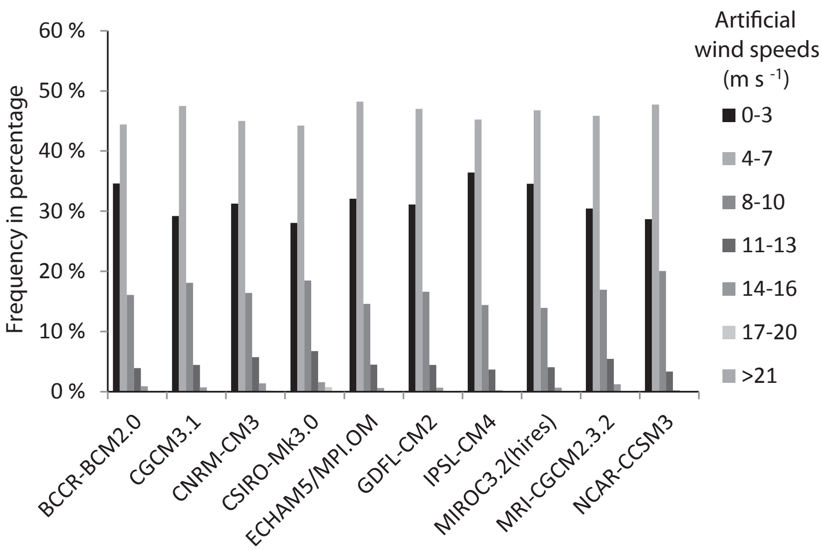

Fig. 2. An example of the distribution of the "artificial" daily wind speeds in Helsinki (grid point 60°N, 25°E) for September–November in 1971–2000 for the individual GCMs.

ods were constructed by deriving these from the 24-hour MSLP and temperature fields. Based on the use of the MSLP and temperature data, it was possible to calculate the geostrophic wind speed $\mathbf{V}_g$ according to:

$$\mathbf{V}_{g24h}^{GCM} = (u_{g24h}^{GCM}, v_{g24h}^{GCM}) = \frac{RT_{daily}}{fp_{daily}} \hat{k} \times \nabla p_{dailly} \quad (2)$$

where R denotes the gas constant of air, T the temperature, f the Coriolis parameter and p the air pressure MSLP. The components u_{g24h}^{GCM} and v_{g24h}^{GCM} were first calculated at the intermediate points on the native grid of each individual GCM. Then the component data were interpolated linearly onto a common 2.5×2.5 degree grid. It was preferable to calculate $\mathbf{V}_g$ based on MSLP and temperature data instead of employing the surface wind speeds because they are less robust as they are diagnostically defined (e.g., Holton 1992, Rööm 1998, Zilitinkevich et al. 2002). The geostrophic wind speeds are not influenced by surface friction and can be used as a rough estimate for the possible gust wind speeds.

The effect of the average roughness (A) on the geostrophic wind was estimated by calculating the ratio between the 5-year return levels of the highest observed wind speeds (V) to the corresponding V_g (5-year return level) based on the average of the 10-GCMs (Table 3) for the closest grid point (see Cressman 1960):

$$A = V / V_g \quad (3)$$

This approach gave us values of A according to the following: 0.6 for Helsinki and Jyväskylä, 0.5 for Joensuu and 0.7 for Rovaniemi. As a comparison, Cressman (1960) suggested that the (spatial) average value of A is around 0.5 for land (England) and 0.7 for ocean (Atlantic Ocean).

In some of the models the wind speeds were systematically higher and in some systematically lower. Therefore, we eliminated first the systematic biases among the models. This was done by adjusting the daily wind speed values of each model according to the 10 GCM average. Then we modified the adjusted daily geostrophic wind speeds of the GCMs by A, i.e. providing, thus, "artificial" daily wind speeds for each individual model (see Fig. 2). These were thought to correspond to the surface wind speeds. To be sure that this was the case, the frequency distributions of the observed daily wind speeds were compared to the frequency distributions of the "artificial" wind speeds. This comparison proved that the "artificial" wind speeds corresponded rather well to the highest daily 3-hourly wind speed readings.

For instance, in Helsinki, the distribution of the highest daily 3-hourly wind speed showed that approximately 10% of the cases were found in the class of 0–3 ms^{-1}, 65% in the class of 4–7 ms^{-1}, 22% in the class of 8–10 ms^{-1} and about 3% in the class of ≥11 ms^{-1}. The corresponding shares considering the 10 GCM ensemble wind speeds were about 25%, 50%, 20% and 5%, respectively.

2.3 Calculation of the 5-Day Cumulative Snow Loads

The 5-day cumulative snow loads were calculated under the CU and CC by employing similar method as used previously by Gregow et al. (2008b), expecting that any precipitation during periods with temperature (T) below 2.3°C was snow. From zero to 2.3°C the loss of snow by melting (%) was expected to increase from zero to 100%. The loss of snow loading (Snow loss %) by wind (U) was expected to be only 0–10% when the wind speeds were < 8 m s^{-1}, whereas between 8 and 16 ms^{-1} the loss of snow by wind was expected to increase to 100%.

The 5-day cumulative snow loads were estimated by employing Eqs. 4–6:

$$\text{Snow loss }(T) = 11.502\, T^{2.6361}/100, \quad \text{when } 0°\text{C} < T < 2.3°\text{C and} \qquad (4)$$
$$= 0, \text{ when } T \le 0°\text{C}$$

$$\text{Snow loss }(U) = (0.0338\, U^3 - 0.217\, U^2 + 0.8065\, U) / 100 \qquad (5)$$

$$\text{Snow load} = \text{Prec}\,[1 - (\text{Snow loss }(U) + \text{Snow loss }(T))] \qquad (6)$$

In Eq. 6, precipitation (Prec) (mm) for each location was converted directly to corresponding mass per unit area (kg m^{-2}).

2.4. Calculation of the Return Levels of Wind Speeds and Snow Loads

The return levels of annual maximum observed wind speeds, observation based cumulative snow loads and modeled geostrophic wind speeds were analysed under the CU for each location by employing the Generalized Extreme Value (GEV) theory formalism. It is an asymptotic treatment of the tails of the distributions (Coles 2001, Castillo et al. 2004) and has a broad applicability to climate variables (e.g. Wehner et al. 2010). We used the block maxima approach by employing the extremes toolkit software package, which has been developed by the National Center for Atmospheric Research, United States (NCAR) (e.g. Katz et al. 2005). In our work, the Broyden–Fletcher–Goldfarb–Shanno (BFGS) method was applied for optimization (see Broyden 1970, Fletcher 1970, Goldfarb 1970, Shanno 1970).

2.5 Calculation of the Soil Frost Depths

The soil frost calculations of the snow free ground were done under the CU and CC by employing the approach adopted from Venäläinen et al. (2001b),

$$D = a \times \sqrt{TS} - b \times TS \qquad (7)$$

where D is the soil frost depth (cm), a and b are coefficients describing the soil properties. TS is the negative of the sum of the daily average temperature from October 1st to when the frost sum accumulation ends in spring. In this study, the coefficients a and b were chosen based on Venäläinen et al. (2001b) as follows: Helsinki $a = 8.7$ and $b = 0.1$, Joensuu $a = 3.61$ and $b = -0.01$, Jyväskylä $a = 2.91$ and $b = -0.04$, Kauhava $a = 5.0$ and $b = 0.03$, Kajaani $a = 2.91$ and $b = -0.04$, Rovaniemi $a = 4.48$ and $b = -0.02$ and Sodankylä $a = 6.52$ and $b = -0.01$. The values of Rovaniemi and Kajaani were estimated separately for this work based on the land type of the site and the values of a and b of the surrounding stations. Additionally, the modeled values of D were also compared to the soil frost depths measured by the Finnish Environmental Institute in winter 2008–2009.

Table 3. The return levels (RL) of the occurrence of the observation based snow loads (S, kg m^{-2}), maximum 10 minute mean wind speeds (W, ms^{-1}) and the 5-yr geostrophic wind speeds based on the 10 GCMs (V_g, ms^{-1}) in 1971–2000 at 95% confidence level.

RL	Helsinki		Joensuu		Jyväskylä		Kajaani		Kauhava		Rovaniemi		Sodankylä	
Yr	S	W/V_g	S	W/V_g	S	W/V_g	S	W/V_g	S	W/V_g	S	W/V_g	S	W/V_g
2	16	16	22	12	21	14	17	14	14	15	21	15	23	12
5	20	17/28	27	13/26	26	15/26	22	15/25	20	16/28	24	16/25	29	13/26
10	23	18	31	14	29	16	25	16	23	17	26	17	33	14

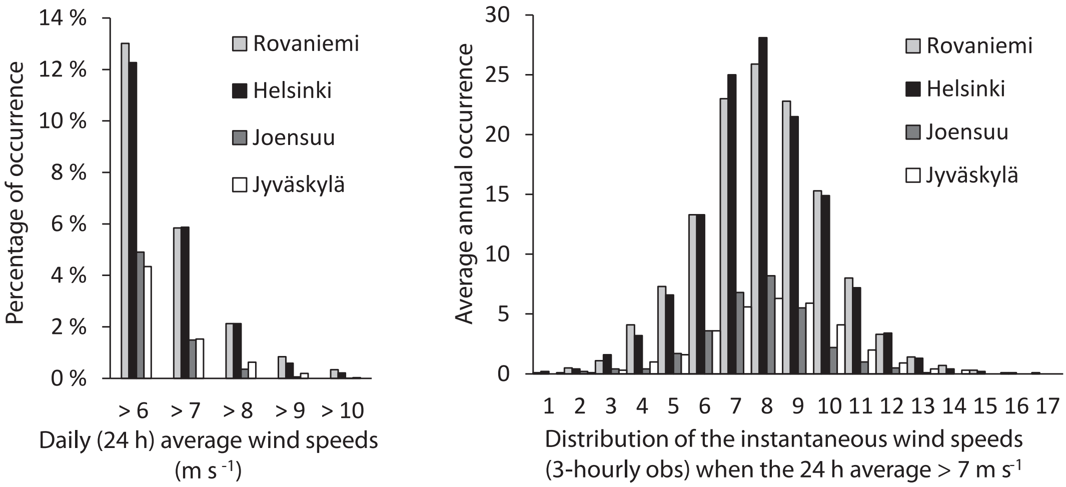

Fig. 3. The percentages of occurrence of daily mean wind speeds in September–May during 1971–2000 (left) and the average annual occurrence (number of occasions) of the 3-hourly instantaneous 10-minute wind speeds that have occurred during the days when the 24 hour average of these (daily mean) has been > 7 m s^{-1}(right).

3 Results

3.1 Occurrence of Different Wind, Snow Load and Soil Frost Conditions under the Current Climate

Return Periods of Strong Winds and Cumulative Snow Loads

The return levels of 2, 5 and 10 years for different wind speeds and the cumulative snow loads are shown in Table 3. In Finland, the annual maximum 10 min mean wind speeds, which occur under the current climate once every 10 years, are about 17–18 m s^{-1} in the southern, western and northern parts of the country (Helsinki, Kauhava, and Rovaniemi) and about 14 m s^{-1} in the east (Joensuu). The geostrophic wind speeds occurring once in five years are approximately 28 m s^{-1} in the southern and western regions (Helsinki, Kauhava), and 25–27 m s^{-1} elsewhere, i.e. being a rough estimate for the surface gust wind speeds related to large scale weather systems of September–May. Furthermore, the two year return levels of cumulative snow loads vary between 14 (Kauhava) and 23 kg m^{-2} (Sodankylä).

Occurrence of the Daily Mean Wind Speeds above 6 m s^{-1}

The percentages of the occurrence of the daily mean wind speeds above 6 m s^{-1}, based on the 3-hourly observations in September–May (soil frost season) during 1971–2000 is shown in Fig. 3. The daily mean wind speed > 7 m s^{-1} is quite rare especially in Joensuu and Jyväskylä (2% occurrence), but also in Helsinki and Rovaniemi (6%).

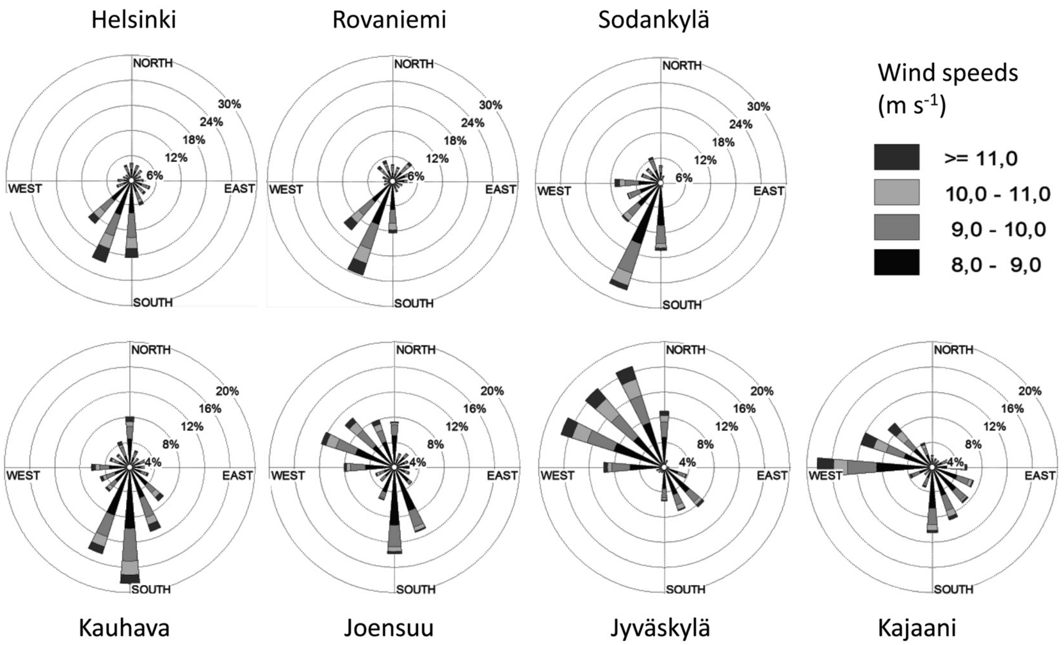

Fig. 4. Wind roses for Helsinki, Rovaniemi, Sodankylä, Kauhava, Joensuu, Jyväskylä and Kajaani based on observed (3-hourly) 10 minute average wind speeds ≥8 m s^{-1} in 1971–2000 in September–May.

During the days when the daily average wind speeds have been > 7 m s^{-1}, the 3-hourly observations have been > 11 m s^{-1} only once or twice per year in Joensuu, 3–4 times in Jyväskylä and 13–14 times in Helsinki and Rovaniemi.

Directional Distribution of Winds

When considering only the observed (instantaneous) wind speeds ≥8 m s^{-1} in 1971–2000 in September–May, in Lapland (Rovaniemi, Sodankylä) and southern Finland (Helsinki), the main wind directions have been from the south or southwest (Fig. 4). Altogether 50–56% of the winds are blowing from these directions. In the western zone (Kauhava), the strongest winds are blowing mainly from the southwest, south and southeast. In the central parts of Finland, westerly to northwesterly and also southerly winds dominate.

The wind speeds and directions are, however, largely influenced by the varying topography, the altitude above the sea level, the proximity of the lakes and the structure of the forests. For example, in Joensuu the largest lake surface is just south of the measurement station, which can result in the dominance of stronger southerly winds. As a comparison, the measurement station of Jyväskylä is situated 139 m above the sea level further away from the lakes. But, west of it the elevation is above 200 m and in north of it only 100 m. Similarly, in the southwest the landscape is rising to around 150 m but in the southeast it sinks to below a hundred meters. This may force the winds blowing from the southwest and west to flow clockwise around the highest elevations. Normally, when encountering such barriers the westerly flow turns and becomes more northwesterly after the barrier, subsequently the air flow continues in a wavelike manner until it reaches equilibrium again.

Occurrence of Soil Frost

During 1971–2009, the snow free soil frost depth was, by the end of December, about 71 cm in southern and central Finland, and about 110–167

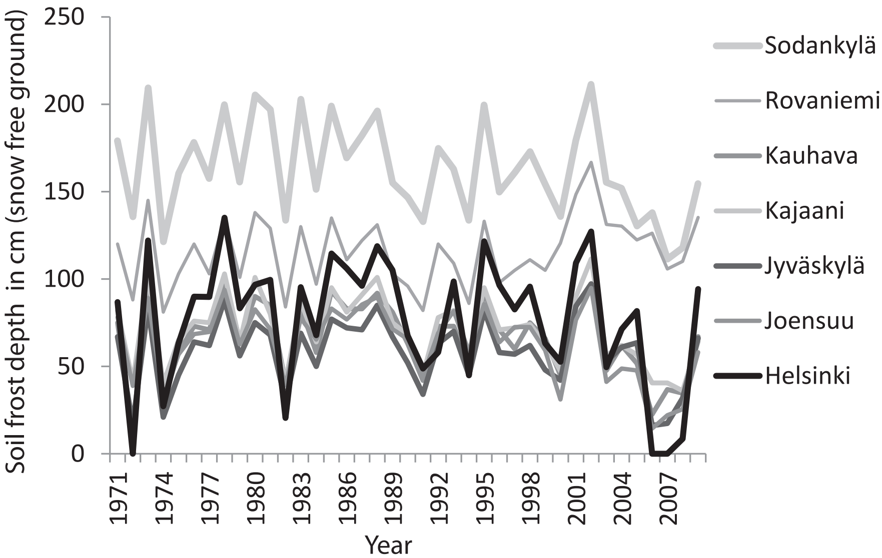

Fig. 5. The snow free soil frost depth on 31st December during 1971–2009. These values are approximately double compared to the actual depths of forest soils that have been measured by the Finnish Environmental Institute.

cm in the north (Fig. 5). As a comparison, in the period of 1980–2009 the corresponding numbers were 67 in southern Finland and 117–162 cm in central Finland, indicating an average decrease of 5–10% in southern and central Finland. At the same time an increase of 5% was observed in Rovaniemi and decrease of 3% in Sodankylä, respectively. Similar changes were also present in January and February (not shown). Most striking in these results is the rather dramatic decrease in the soil frost depth that has taken place during the period of 2000–2009. Comparing the mean soil frost depths in 2000–2009 and 1971–2000, the decrease in December 15th, January 15th and February 15th is approximately 25% in southern Finland and up to 10% in Sodankylä, whereas in Rovaniemi an increase of around 10% occurred. However, the years 2000–2009 have been the warmest ones on record on a global scale according to the World's Meteorological Organization (WMO) and in Finland (Tietäväinen et al. 2010).

Concurrent Occurrence of Wind, Snow Loading and Soil Frost

In general, about 76–93% of the wind speeds were <8 m s^{-1} in September–May in the seven locations studied. The wind speeds ≥8 m s^{-1} occurred when the snow free soil frost was ≤60 cm in Helsinki, Kauhava and Rovaniemi in 7–11% and in other locations in 2–5% of all the studied cases (Fig. 6). Thus, the potential risk for uprooting seems to be largest in southern and western Finland and in western part of Lapland.

Regardless of the snow loads, the concurrent wind speeds were <8 m s^{-1} in 98% of the studied cases. The snow loads were also <10 kg m^{-2} in Helsinki, Kauhava, Kajaani and Rovaniemi in 88–94% of the cases, while in Joensuu, Jyväskylä and Sodankylä, the corresponding numbers were 72–80%. The share of the occurrence of snow loads of 10–20 kg m^{-2} was 20–25% in Joensuu, Jyväskylä, Sodankylä, whereas in the other locations it was approximately 5–10%. Wind speeds during heavier snow loads were very rarely above 8 m s^{-1} (also due to the snow load model properties). Additionally, the typical snow loads of 10–20 kg m^{-2} have taken place when the soil frost (snow free) has been >60 cm (Fig. 7). Such cases occur about four times more often in Sodankylä than in Helsinki and Kauhava. Heavier snow loads (>20 kg m^{-2}) were most common in Sodankylä, Joensuu and Jyväskylä with the soil frost ≤60 cm. In Kauhava, these cases have been rare and occurred only 16 times in 30 years. All in all, the potential risk for uprooting due to the combination of heavy snow fall and unfrozen soil seems to be most pronounced in the surroundings of Jyväskylä, Joensuu and Kajaani, interpreted as central and eastern Finland.

Wind speeds >8 m s^{-1} with snow loads >10 kg m^{-2} have taken place in the northern and eastern parts of Finland once in two years and elsewhere approximately once in three years (Fig. 8). In eastern Finland, the snow free soil frost has been at maximum of 60 cm in 80% of such cases, while the corresponding number is for the coastal zone and central part 60% and for the northern part 50%. The heaviest snow loads of 35–50 kg m^{-2} (not shown) have occurred in Kauhava, Joensuu, Jyväskylä and Sodankylä mostly with wind speeds of 4–7 m s^{-1}.

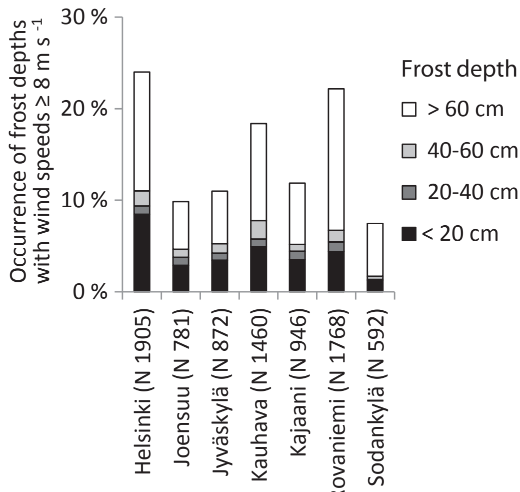

Fig. 6. The percentage occurrence of (snow free) soil frost depths when the concurrent wind speeds have been ≥8 m s^{-1} in 1971–2000 in September–May. The total number of days with such snow loads is marked with N.

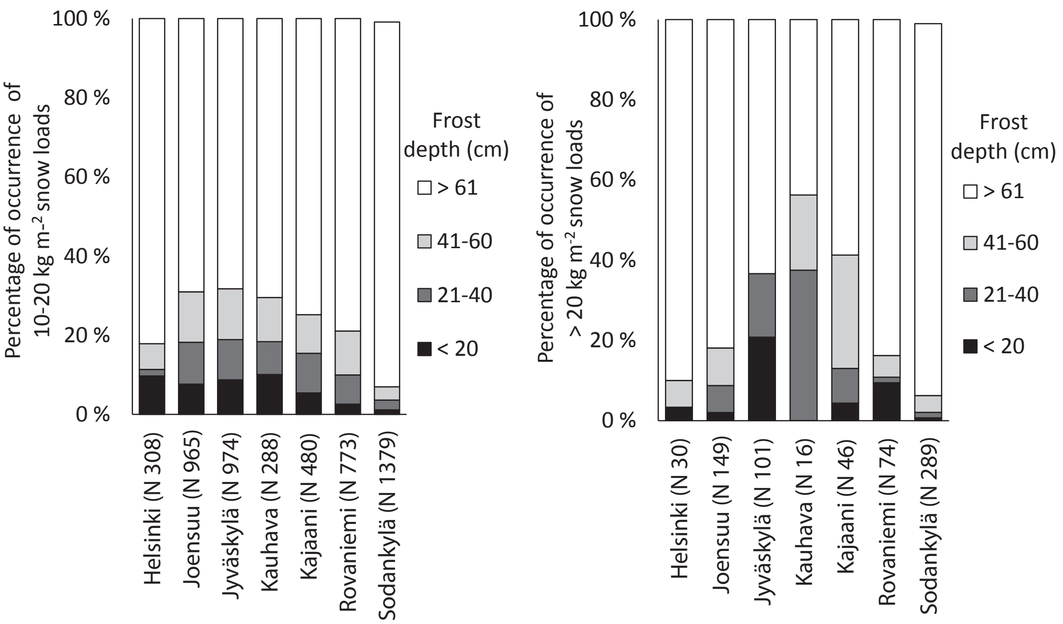

Fig. 7. Occurrence of snow free soil frost with snow loads of 10–20 (left) and >20 kg m^{-2} (right) with the total number of days with such snow loads marked with N in 1971–2000.

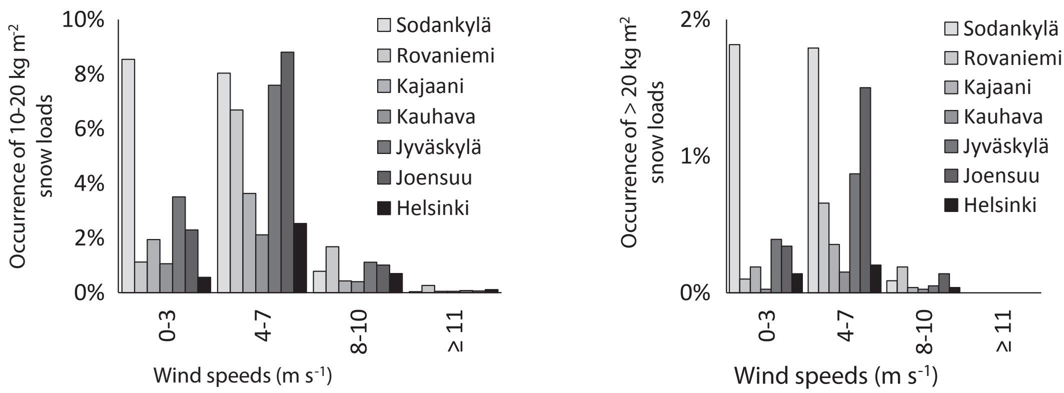

Fig. 8. The concurrent occurrence of 10–20 kg m^{-2} (left) and >20 kg m^{-2} daily cumulative snow loads (right) and the highest observed daily 10-minute instantaneous wind speed (m s^{-1}), based on eight observations made at every three hours in each day in 1971–2000.

Table 4. The mean projections as averaged for 2046–65 and 2081–2100 under the CC compared to CU for the average daily wind speed (m s^{-1}), depth of soil frost and cumulative snow load of 5 days (kg m^{-2}) in September–May. The corresponding changes are shown for the daily temperature (in degree Celsius) and the daily precipitation (%).

	Average over the changes by 2046–65 and by 2081–100				
	Wind, daily	Soil frost, daily	T, daily	Prec, daily	Snow load, 5 day
Helsinki	2%	–82%	3.6	11%	–50%
Joensuu	2%	–54%	4.0	22%	–18%
Jyväskylä	3%	–66%	3.8	23%	–26%
Rovaniemi	2%	–44%	4.3	14%	–5%

3.2 Projected Changes in the Occurrence of Average Daily Wind Speeds, 5-Day Cumulative Snow Loads and Soil Frost under the A1B Scenario

Percentage Changes in Wind Speeds, Snow Loads and Soil Frost

Comparison of the climate projections for the periods of 2046–65 and 2081–2100 with the current climate of 1971–2000 shows that towards the end of this century there will be approximately a 3.6–4.3 degrees increase in daily mean temperature, the increase being largest in the north (Table 4). The mean daily precipitation is projected to increase by 11–14% in Helsinki and Rovaniemi, and by 22–23% in Jyväskylä and Joensuu. Furthermore, in September–May the average daily wind speeds will increase only a few percent in Finland (Table 3). The soil frost depth will, in general, decrease about 44% in Rovaniemi, 54% in Joensuu and 66% in Jyväskylä and the most, up to 82%, in Helsinki until 2100. At the same time, the overall snow loading is projected to decrease by 5% in Rovaniemi, 18% in Joensuu, 26% in in Jyväskylä and 55% in Helsinki.

Changes in Different Snow Load Classes

The possible changes in the share of various snow load classes are shown in Table 5. The overall occurrence of snow loading is decreasing in the future, especially due to decrease of the occurrence of the lower snow loads of 10–20 kg m^{-2}. For instance, in Helsinki the share of these is expected to decrease by about 60%, in Jyväskylä about 40% and in Rovaniemi about 15% in 2046–

Table 5. The projected changes (%) in the occurrence of cumulative snow loads of 5-days in September–May from the current climate (1971–2000) to the future periods of 2046–65 and 2081–2100 when assuming the A1B-scenario.

1971–2000 → 2046–2065	Helsinki	Joensuu	Jyväskylä	Rovaniemi
10–20 kg m^{-2}	–63%	–38%	–37%	–15%
20–30 kg m^{-2}	–72%	22%	–27%	35%
30– kg m^{-2}	40%	45%	–89%	0%
1971–2000 → 2081–2100	**Helsinki**	**Joensuu**	**Jyväskylä**	**Rovaniemi**
10–20 kg m^{-2}	–70%	–50%	–59%	–36%
20–30 kg m^{-2}	–61%	–40%	–29%	–5%
30– kg m^{-2}	–80%	45%	–44%	–67%

Table 6. Changes in the occurrence of snow loads >20 kg m^{-2} and the concurrent occurrence of daily average GCM wind speeds >6 m s^{-1} when snow free soil frost is ≤60 cm (potential risk for uprooting) and >60 cm (potential risk for stem breakage).

Changes in the risk for uprooting	Helsinki	Joensuu	Jyväskylä	Rovaniemi
1971–2000 → 2046–2065	18%	0%	13%	–18%
1971–2000 → 2081–2100	18%	100%	25%	0%
Changes in the risk for stem breakage	**Helsinki**	**Joensuu**	**Jyväskylä**	**Rovaniemi**
1971–2000 → 2046–2065	–92%	0%	–100%	75%
1971–2000 → 2081–2100	–92%	–100%	–100%	63%

65 and somewhat more in 2081–2100. However, the occurrence of heavier snow loads of 20–30 kg m^{-2} in Rovaniemi and >30 kg m^{-2} in Helsinki and Joensuu are projected to increase in 2046–65. In 2081–2100, the decline in both the lower and the heavier snow loads is apparent, with the exception of Joensuu where the heaviest snow loads are projected to be more common in the future than under the current climate.

Changes in the Frost Categories and the Frost Season Length

Under the current climate (1971–2000), in Helsinki and Jyväskylä, the soil is frozen in the deeper layers for approximately four months, in Joensuu five months and in Rovaniemi for six–seven months (Fig. 9). By the middle of this century the corresponding numbers are projected to be one to two months, three months and six months, respectively. Towards the end of this century, the deeper soil frost classes supporting the anchorage of trees will nearly disappear in southern and central Finland. In the north, the duration of such soil frost depths is projected to be one to two months shorter than under the current climate. In the east, the decrease is three months on average. This indicates a decrease of 25 and 75% compared to the current climate, respectively.

Combined Occurrence of Wind, Snow Loads and Soil Frost Conditions with Implications to the Risk of Wind and Snow Induced Damages

In this work we also analysed in detail the concurrent occurrence of average daily wind speed >6 m s^{-1}, snow load >20 kg m^{-2} with (case 1) snow free soil frost ≤60 cm and (case 2) >60 cm for the periods of 2046–65 and 2081–2100. The projected changes for case 1 and 2 are considered to represent the outlook in the occurrence of climatic conditions indicating potential risk to uprooting and stem breakage. These changes are shown in percentages in Table 6. According to our work,

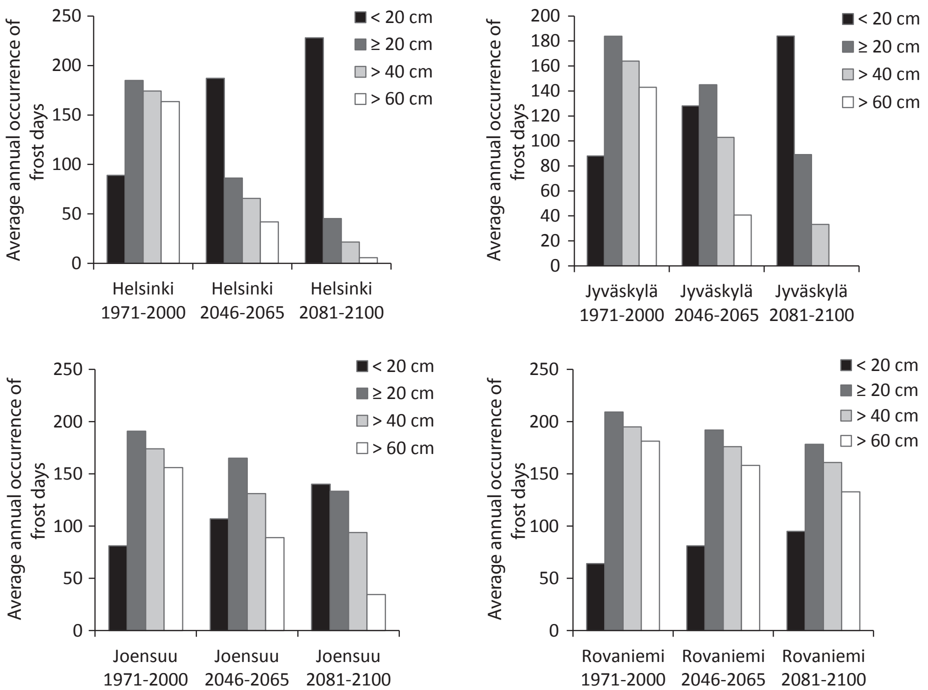

Fig. 9. The average annual occurrence of the various (snow free) soil frost categories < 20 cm, ≥20 cm, >40 cm and >60 cm based only on the analyses of the GCM data. The class of >60 cm is expected to provide sufficient support for the anchorage of trees (against uprooting).

the occurrence of conditions indicating risk of uprooting will increase especially in the eastern part of Finland and somewhat in the southern and central parts of the country. In the north, such conditions could possibly even decrease in the next decades. In the north, the risk of stem breakage, on the other hand, is projected to increase. Elsewhere, the potential risk of stem breakage based on the analyzed climatic conditions will clearly decrease.

4 Discussion and Conclusions

4.1 Evaluation of the Methodologies Applied

In this work, we attempted to study the concurrent occurrence of different wind speeds, snow loads and soil frost categories. The different combinations of these can have severe implications to forests and forestry under the current and changing climatic conditions in Finland. For this purpose, we used the most recent meteorological datasets available from the Finnish Meteorological Institute for the current climate (observations for 1970–2009) and the A1B-climate scenario (Nakicenovic et al. 2000) for 2046–65 and 2081–2100. In this work, the future projections for daily temperature and precipitation were created from the current climate (1971–2000) by using the stochastic weather generator LARS-WG (Racsko et al. 1991, Semenov and Barrow 2002, Semenov 2007, Semenov and Sratonovitch 2010), the delta change method (Agresti 2002) and the expected changes for daily temperature and precipitation based on previous work by Jylhä et al. (2009). For the future projections of wind climate, we analyzed the daily geostrophic wind speeds.

The snow loads in this work were calculated as cumulative sums by employing the snow load model that uses inputs of precipitation, temperature and wind speed. In this model, the wearing of snow starts directly if there is any wind, independent of temperature. However, in reality dry and wet snow are transported differently as a result of the snow pack properties (snow particle cohesion, bonding and kinetic friction) starting with wind speeds of, on average, 4–7 m s^{-1} (Li and Pomeroy 1997). Additionally, our model does not consider the drifting of wet or dry snow that, due to turbulent winds, can actually increase the loading during a snow fall episode in forests (Degaetano and Rourke 2003). Neither is the snow hardening proportional to the snow age (Yong and Metaxas 1985) included in the current calculations. Despite these limitations, the simulated snow loads have been found to produce the temporal variation of the snow loads relatively well (Gregow et al. 2008b). In the future development of the snow load model it would be beneficial to consider especially the impact of humidity which can cause ice loadings and otherwise make the snow heavier (proportional to elevation).

For the future projections of the wind climate, we preferred to analyze the daily geostrophic wind speeds (derived from MSLP and temperature data) instead of employing the surface wind speeds. The surface winds are dependent on surface roughness (i.e. surface properties such as land-sea proportions, sea ice cover), and are parametrized in the GCMs in many different ways. On the contrary, the MSLP and temperature fields are not that sensitive to parametrization and are therefore more easily comparable with each other. In general, the distribution of the wind speeds in the individual climate models was found to be qualitatively good. This was seen when the frequency distributions of the observed daily wind speeds were compared to the frequency distributions of the "artificial" wind speeds (estimate for the surface wind speed based on the average roughness and geostrophic wind speed). This comparison also revealed that the GCM ensemble had a smaller amount of weak wind speeds than was present in the observations. Thus the GCM ensemble gives smaller amounts of snow loading than would be obtained by utilizing the observed wind speeds. Nonetheless, as the wind speeds of the four grid points (Helsinki, Jyväskylä, Joensuu and Rovaniemi) were calculated in the same manner for the current climate as for the future, the projected changes in relative terms could be estimated consistently.

The 5-year return levels of annual maximum observed wind speeds and modeled geostrophic wind speeds, as well as the cumulative snow loading were analyzed under the current climate for each location by employing the Generalized Extreme Value (GEV) theory formalism. Due to the relatively short time series behind these analyses, our findings are in this sense most valid for the return periods of 2, 5 and 10 years. Additionally, in this work we compared the 5-year return levels of the highest observed wind speeds to the corresponding geostrophic ones derived from the ten GCMs. We found that our estimate for the average spatial roughness corresponded well to the findings of Cressman (1960).

The soil frost depth on snow free ground was calculated by applying the method of Venäläinen et al. (2001b). The snow free soil frost depths that were compared to the measurements of the soil frost depths for 2008–2009 from the Finnish Environmental Institute were found to correspond to approximately double the actual depths of forest soils. The choice of data and the fact that the actual depths of forest soils depend on the soil type and heat capacity made us use the snow free soil frost model. The use of sophisticated forest soil frost models would have needed much more detailed input data on soil (e.g. soil type and texture) and more detailed climatic data (e.g. humidity, cloudiness and radiation). Such information has been included in the soil frost projections of Kellomäki et al. (2010), based on the use of the forest ecosystem model (e.g. FinnFor, see Kellomäki et al. 1993).

4.2 Evaluation of the Results

Under the current climate, the typical annual snow loads in Finland, 10–20 kg m^{-2}, have taken place mostly when the snow free soil frost depth has been larger than 60 cm. The annual occurrence of such episodes has been largest in northern and eastern Finland and smallest in southern and western Finland. Nearly in all of these snow load cases (98%), the wind speeds have been lower than 8 m s^{-1} (also due to the limits used in the snow load model). The risk of uprooting due to poorly frozen soil and strong winds seems to be largest in southern and western Finland as well as in the western part of Lapland. On the other hand, the risk to uprooting due to the combined occurrence of heavy snow fall and unfrozen soil seems to be most pronounced in the surroundings of Jyväskylä, Joensuu and Kajaani interpreted as central and eastern Finland. Characteristic of Helsinki, Jyväskylä, Kauhava, Kajaani and Rovaniemi is that, for example, once in 10 years the snow load and wind speed have, under the current climate, been approximately 22–29 kg m^{-2} and 16–18 m s^{-1}, respectively. In Joensuu and Sodankylä, the corresponding values have been 31–33 kg m^{-2} and 14 m s^{-1}. In the future, heavy snow loads of > 30 kg m^{-2} may become more common in Helsinki and Joensuu region considered as southern and eastern Finland, despite the fact that the average cumulative 5-day snow loads are projected to decrease in these areas by 18 to 50%, respectively. However, the occurrence of strong winds is not expected to increase significantly based on our findings.

The decade 2000–2009 has been the warmest on record globally according to the World's Meteorological Organization (WMO), also in Finland (Tietäväinen et al. 2010), which could also be seen in the rather strong decrease in the modeled soil frost depths in December–February. On average, the soil frost depths are 25% lower in the southern areas and around 10% lower in Sodankylä during 2000–2009 compared to 1971–2000. However, in Rovaniemi an increase of approximately 10% has taken place. In our work, the projections for the future show that those soil frost depths which nowadays provide support for the anchorage of trees will nearly disappear in southern and central Finland during this century. In the east, the occurrence of these soil frost depths can decrease by three months and in the north by one to two months compared to nowadays (i.e. such frost depths are projected to occur in the future from one to four months).

The occurrence of soil frost, which is crucial especially for the anchorage of trees during the windiest time of the year in Finnish conditions (Peltola et al. 2010), is also important for the carrying capacity of soils and thus, for harvesting operations (e.g. Kellomäki et al. 2010). There is also risk of the soils becoming wetter, when freezing no longer occurs and the precipitation increases in the form of rain. Similar results have been found, for example, in the soil frost studies of Peltola et al. (1999), Venäläinen et al. (2001a,b) and Kellomäki et al. (2010).

Based on our work, as a result of combined changes in the occurrence of wind, snow loading and soil frost, the risk of climatic conditions making conifers liable to uprooting are projected to increase clearly in southern, central and eastern Finland. This is because the occurrence of such soil frost depths, will, in the future, nearly disappear especially in southern and central Finland. In the north, the risk of stem breakage is projected to become more pronounced under snow loading of >20 kg m^{-2}. However, forest dynamics is affected, in addition to climatic conditions, also by management (e.g. preference of tree species, spacing, thinning and rotation length), and therefore, by proper management it is possible to mitigate the level of risks to some degree (see e.g. Peltola et al. 2010). In the windiest regions and near the topographic barriers that can influence the direction of the air flow, the wind directions should be considered in forest planning and risk management.

4.3 Conclusions

To conclude, any attempts to develop sustainable management practices in order to reduce the above mentioned risks in forestry require regional information also on climate parameters under the current and changing conditions. The occurrence of strong winds, heavy snow loading and soil frost in interaction can have severe implications to forests and forestry as well as for the society, in general. In this sense, despite some uncertainties that exist related to our work, our findings can serve as valuable support when trying to minimize the wind and snow induced damages to Finnish forests and forestry. However, the accurate projections of the future changes in strong winds and/or snow loading, as well as in soil frost occurrence, as caused by global warming are challenging. This is partly because the deviation among the different GCMs in regard to the probabilities of the projected changes is still large. Furthermore, the natural variation in climate has been estimated to increase in the future (IPCC). That would be important to consider next in the calculations. Future research should, thus, investigate, especially the uncertainties related to weather as well as climate projections.

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