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IMPACTS OF STRONG WINDS, HEAVY SNOW LOADS AND SOIL FROST CONDITIONS ON THE RISKS TO FORESTS IN NORTHERN EUROPE

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ACADEMIC DISSERTATION

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Title
Impacts of strong winds, heavy snow loads and soil frost conditions on the risks to forests in Northern Europe

Abstract

The aim of this work was to study the potential impacts of strong winds, heavy snow loads, and soil frost conditions on the risks to forests in northern Europe under the current and changing climate (until 2100), with the main focus on Finland. More specifically, the analyses concentrated on: i) changes in the occurrence of strong winds, heavy snow loads, and unfrozen soil conditions in Finland, ii) regional risks to Finnish forests from heavy snow loads and strong winds, iii) the mean and extreme geostrophic wind speeds in Northern Europe, and iv) estimation of windstorm-related timber losses in Europe in 1960-2011 using the geostrophic and ageostrophic isallobaric winds as a basis for the analyses.

This work employed the meteorological measurements made by the Finnish Meteorological Institute (FMI) between 1961-2009, the datasets from the Finnish National Forest Inventory and the EFIATLANTIC storm catalogue, a number of global climate model (GCM) simulation runs using different greenhouse gas (GHG) emission scenarios (A1B, A2, and B1) and re-analyzed weather datasets ERA-40 and ERA-Interim. The occurrence and depths of soil frost were studied with a model that simulates the freezing of the snow-free ground. The occurrence of large snow loads was estimated with the cumulative snow load approach. The analyses of the risks from snow and/or wind to forests were based on simulations done by the ecosystem model SIMA, the mechanistic model HWIND, and a new regression fit between storm wind impact and timber losses in Europe.

According to this work, the growth of Finnish forests is expected to increase under the changing climate. Concurrently, the tree species distribution may also change, which affects the potential risks to forests from wind and snow. In the current climate, strong mean wind speeds of about 17-18 m s^{-1} have occurred approximately once in 10 years in Finland (in October-February) and caused wind damages. In this work, wind speeds induced by intense cyclones were also found to correlate well with primary losses of timber. The annual maximum soil frost depth has also decreased 5-10% in the period 1980-2009 compared to the period 1971-2000 in southern and central Finland. Under the future climate projections, the soil is expected to hardly freeze at all in southern and central Finland by 2100. Mean and extreme geostrophic wind speeds are also projected to increase during September-April slightly by 2100. Furthermore, days with heavy snow loads may still occur in the near future. To conclude, wind-induced risks to forests in particular may increase in Finland and elsewhere in Northern Europe in the forthcoming decades. However, proper and timely management of forests could help reduce at least to some degree wind-induced risks to forests in the future.

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Nimike

Voimakkaiden tuulten, lumikuormien ja roudan esiintymisen vaikutus metsien tuhoriskeihin Pohjois-Euroopassa

Tiivistelmä

Tämän työn tavoitteena oli tutkia voimakkaiden tuulten, lumikuormien ja roudan esiintymisen mahdollisia vaikutuksia metsien tuhoriskeihin Pohjois-Euroopassa. Tarkastelut tehtiin nyky- ja muuttuvalle ilmastolle aina vuoteen 2100 asti. Pääpaino tutkimuksessa oli Suomessa. Työssä analysoitiin i) voimakkaan tuulen, lumikuormien ja routaolojen esiintymisessä tapahtuvia muutoksia Suomessa, ii) Suomen metsiin kohdistuvia alueellisia tuuli- ja lumituhoriskejä, iii) ilmastonmuutoksen vaikutusta keskimääräisiin ja äärimmäisiin geostrofisiin tuuliin Pohjois-Euroopassa ja iv) Euroopan primääristen metsätuhojen ja myrskyissä esiintyneiden geostrofisten ja ageostrofisen isallobaaristen tuulten välistä yhteyttä 1960–2011.

Työssä käytettiin Ilmatieteen laitoksen havaintoaineistoa 1961–2009, Metsäntutkimuslaitoksen valtakunnan metsien inventointitietoja (METLA), Eurooppalaista metsien myrskytuhotietokantaa (EFIATLANTIC) ja lukuisia maailmanlaajuisia ilmastomalleja huomioiden eri skenaariot (A1B, A2 ja B1). Tämän lisäksi käytettiin uusanalysoituja meteorologisia aineistoja (reanalyysejä) ERA-40 ja ERA-Interim. Roudan syvyyksiä tutkittiin mallilla, joka laskee lumettoman maan jäätymistä. Puiden lumikuormien esiintymistä arvioitiin kumulatiivisella lumikuormamallilla. Metsiin kohdistuvia lumikuormien ja tuulten aiheuttamia riskejä analysoitiin SIMA-ekosysteemimallilla ja mekanistisella HWIND-mallilla. Tämän lisäksi kehitettiin regressioyhtälö, jolla voitiin arvioida metsien puustotuhojen määrää myrskytuulten perusteella Euroopassa.

Työn perusteella Suomen metsien kasvu tulee lisääntymään ilmaston lämmetessä ja lisäksi puulajien jakauma voi muuttua. Tällä voi olla vaikutusta siihen, millaisia lumi- ja tuulituhoja metsissä tulevaisuudessa mahdollisesti esiintyy. Nykyilmastossa, 10-minuutin keskituuli, joka esiintyy keskimäärin kerran kymmenessä vuodessa, on voimakkaimmillaan noin 17–18 ms^{-1} maan etelä- ja länsiosan sisämaassa. Tyypillisimmin voimakkaita tuulia esiintyy lokakuusta helmikuuhun ulottuvalla jaksolla. Euroopan myrskyjen laajuudella, tuulen nopeudella, ja primääristen metsätuhojen suuruudella on selvä korrelaatio. Suomen etelä- ja keskiosassa roudan syvyydet ovat pienentyneet talvella 5-10 % verrattaessa jaksoa 1980–2009 jaksoon 1971–2000. Mikäli ilmaston lämpeneminen jatkuu, maan etelä- ja keskiosa muuttuvat vuosisadan loppuun mennessä vähitellen roudattomiksi. Lumikuormat voivat vielä lähivuosikymmeninä olla suuria maan etelä- ja keskiosassa, mutta loppuvuosisadalla suuria lumikuormia esiintynee enää pohjoisessa. Suomessa keskimääräiset ja äärimmäiset geostrofiset tuulet voimistuvat syyskuu-huhtikuu välisenä aikana vuoteen 2100 mennessä. Muutos on kuitenkin vain muutaman prosentin luokkaa. Kaikki tulokset vahvistavat käsitystä siitä, että erityisesti metsiin kohdistuva tuuliriski on mitä todennäköisimmin kasvamassa niin Suomessa kuin muualla Pohjois-Euroopassa. Tämä edellyttää tuhoriskien huomioimista metsien hoidossa.

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LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following Papers referred to in the text by the Roman numerals I-V:

I Gregow, H., Peltola, H., Laapas, M., Saku, S., Venäläinen, A. 2011. Combined occurrence of wind, snow loading and soil frost with implications for risks to forestry in Finland under the current and changing climatic conditions. *Silva Fennica,* **45(1)**, 35–54.

II Kilpeläinen, A., Gregow, H., Strandman, H., Kellomäki, S., Venäläinen, A. and Peltola, H. 2010. Impacts of climate change on the risk of snow-induced forest damage in Finland. *Climatic Change*, **99 (1-2)**, 193–209.

III Peltola, H., Ikonen, V-P., Gregow, H., Strandman, H., Kilpeläinen, A., Venäläinen, A., Kellomäki, S. 2010. Impacts of climate change on the forest dynamics and timber production with implications on the regional risks of wind-induced damage to forests in Finland. *Forest Ecology and Management,* **260 (5)**, 833–845.

IV Gregow, H., Ruosteenoja, K., Pimenoff, N. and Jylhä, K. 2012. Changes in the mean and extreme geostrophic wind speeds in Northern Europe until 2100 based on nine global climate models. *International Journal of Climatology,* **32**, 1834–1846. doi: 10.1002/joc.2398

V Gregow, H., Jokinen, P., Venäläinen, A., Laaksonen, A., 2013. Estimating windstorm-related forest damage in Europe from 1960–2011 using geostrophic and ageostrophic isallobaric winds (Manuscript under revision for International Journal of Climatology).

Hilppa Gregow had the main responsibility for the planning, data analyses and writing of Papers I, IV, and V as a corresponding author. In Paper I, M.Sc. Mikko Laapas calculated the daily temperature and precipitation values from the monthly data by employing the weather generator LARS-WG. In Paper IV, Dos. Kimmo Ruosteenoja did the pre-processing of the climate model data and M.Sc. Natalia Korhonen (née Pimenoff) performed the gridded extreme value calculations. In Paper V, the ERA-40 and ERA-Interim winds were calculated by M.Sc. Pauli Jokinen. In Paper II Hilppa Gregow participated in discussion of the results and writing the snow load model related matters. In Paper III, Hilppa Gregow took part in the data analyses, discussion, and writing of the results. The co-authors of Papers I, IV, and V have participated in the work by commenting and improving the manuscripts.

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Helsinki, May 2013

Hilppa Gregow

CONTENTS

1. INTRODUCTION

1.1 OCCURRENCE OF WIND AND SNOW DAMAGES

Wind and snow climate have significant influence on the forest ecosystems in central and northern Europe. Recurrent damages by strong winds (Fig. 1) and heavy snow loads (see Ulbrich et al. 2001; Dobbertin 2002; Schönenberger 2002; Brüdl and Rickli 2002; Alexandersson 2005; Matulla et al. 2007) cause large economic losses in managed forests (see e.g., Nilsson et al. 2004; Bengtsson and Nilsson 2007) due to reduced yields of recoverable timber and increased costs of unscheduled harvesting. Damages caused by strong winds and heavy snow loads also lead to deviations from the original forest management plans.

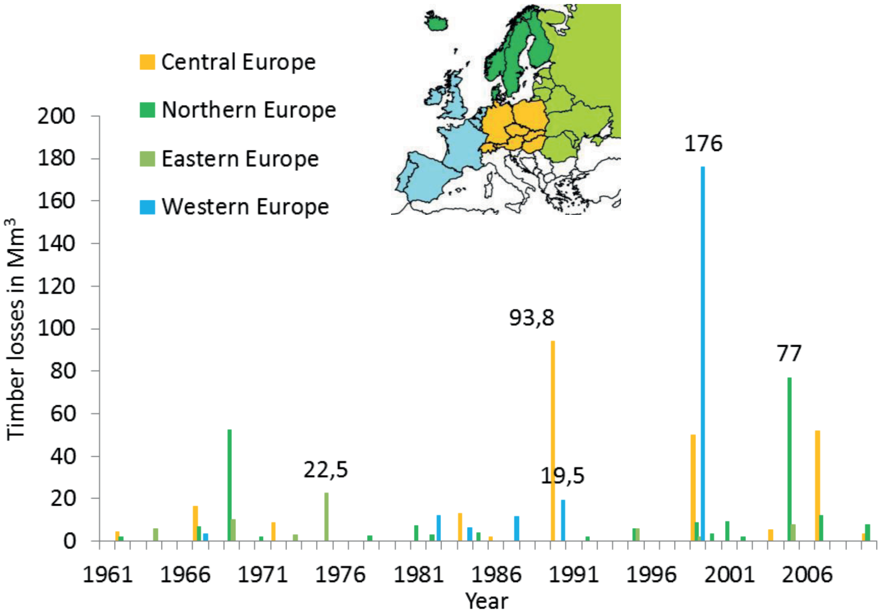

Fig. 1. Losses of timber in forests due to storms in Europe in 1960-2010 based on the primary damages reported in the EFIATLANTIC storm catalogue.

Because the growing stocks of the European forests are increasing (Schelhaas et al. 2003) and the storm tracks and impacts are changing due to ongoing global warming (Leckebusch and Ulbrich 2004; Bengtsson et al. 2006, 2009; Pinto et al. 2007; Leckebusch et al. 2008; Ulbrich et al. 2008, 2009; Harvey et al. 2012), the necessity arises to consider the vulnerability of forests to wind- and snow-induced damage, especially in the regions at highest risk of damage. However, as shown by Blennow et al. (2010) and Pinto et al. (2012), the estimates of wind risks may differ greatly, depending on the climate model and greenhouse gas scenario used as well as the storm time series studied. This uncertainty thus has to be taken into consideration when the results are interpreted and strategies for adaptation for such risks are created.

The susceptibility of tree stands to wind and snow damage is affected by forest structure, site conditions, forest management, and wind and snow extremes. Important factors are the tree and stand characteristics such as tree species, tree height, diameter at breast height, crown area, rooting depth and width, and soil type and topography (see, e.g., Peltola 2006). The potential of wind- and snow-induced damage is often highest if sudden changes happen in the exposure of trees. New forest edges with trees that have not been acclimatized to strong winds are very vulnerable, as are unthinned dense stands with large snow loads (see Neustein 1965; Lohmander and Helles 1987; Peltola 1996; Gardiner and Stacey 1995; Peltola et al. 1997, 1999a; Talkkari et al. 2000; Dupont and Brunet 2008; Nicoll et al. 2008). Trees that suffer from these damages are also often targets for insect attacks (see Nykänen et al. 1997; Valinger and Fridman 1997; Schönenberger 2002; Jönsson et al. 2009; Jönsson and Bärring 2011).

Until now, the strongest winds and largest wind damage events in Finland have usually occurred in the windiest season, from late autumn to early spring (September-April) (Gregow et al. 2008). Fortunately, during this period, the soil is often frozen (Soveri and Varjo 1977; Huttunen and Soveri 1993; Solantie 1998), anchoring the trees solidly in the ground and making them less vulnerable to uprooting. On the other hand, the risk for snow damage in terms of stem breakage is common in winter. Strong winds are possible also during the warmest season. For example, in July-August 2010, Finland experienced four fierce summer storms in the warmest summer in 100 years, which caused about as much vast destruction (8 Mm^3) as the storms “Pyry” and “Janika” (7,3 Mm^3) in October-November of 2001.

1.2 DAMAGE TYPES AND FUTURE RISKS

Wind effects on individual trees are caused by average wind speed and its direction, duration, and gustiness. In Finland, even relatively low mean (10 minutes) wind speeds of 9-13 ms^{-1} can cause damage, especially if they are related to additional snow loading (Talkkari et al. 2000; Pellikka and Järvenpää 2003; Gregow et al. 2008). Wind damage often occurs near the sea and large lakes, too. In these locations, the wind speeds are typically higher compared to other areas due to the lower surface roughness compared to the surrounding forested areas (e.g., Gregow et al. 2008). Stem breakage may be even more likely than uprooting if the wind loading to the crown area increases suddenly due to either strong wind gusts or moderate winds with concurrent snow loads on tree crowns such as > 20 kg m^{-2} (Ancelin et al. 2004; Peltola et al. 2006).

Norway spruce (*Picea abies*) has usually been considered the most vulnerable tree species to wind-induced damage in Finnish conditions because of its relatively shallow roots (see Laiho 1987; Peltola et al. 1999a; Ihalainen and Ahola 2003). On the other hand, forests dominated by Scots pine (*Pinus sylvestris*) and silver and downy birch (*Betula pendula* and *Betula pubescens*) are usually more vulnerable to snow-induced damage such as stem bending or breakage when the soil is frozen (Valinger et al. 1993; Valinger and Lundqvist 1994; Solantie 1994). If the soil is not frozen, trees can also be uprooted.

Snow loading is most likely when the air temperature is between -3 and +1 °C, the winds are light, and there is precipitation (snowfall, sleet, freezing rain). In such conditions, snowfall can effectively stick to tree trunks and branches (Solantie 1983, 1994; Valinger and Lundqvist 1994; Quine 2000). In Finland, large snow loads are common, especially in the eastern and northern parts of the country and at higher altitudes (Gregow et al. 2008).

By the end of this century, the projections of future climate based on global climate models (GCM) and regional climate models (RCM) run under the different greenhouse gas scenarios (Fig. 2) indicate that the annual temperature will increase 2-7 ºC and annual precipitation will increase concurrently by 6-37% in Finland (Jylhä et al. 2004, 2009; Ruosteenoja et al. 2005).

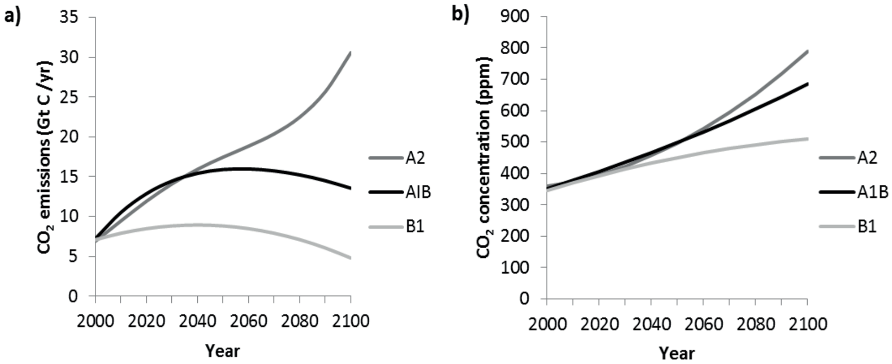

Fig. 2. Emissions and concentrations of CO_2 *during this century depending on the materializing of the SRES scenarios A2, A1B, and B1 (drawn based on Nakićenović et al. 2000).*

The increases in temperature and precipitation will be accompanied by a decrease in snow cover, especially in November and March-April (Jylhä et al. 2004; Carter et al. 2005; Ruosteenoja et al. 2005). On the other hand, based on various recent climate model simulations (see, e.g., Räisänen and Joelsson 2001; Räisänen et al. 2003, 2004, 2008, 2012), warming of the climate can result in larger daily snowfall amounts. Additionally, conditions in which the attachment of snow and the accumulation of snow on tree crowns are concurrently enhanced may even increase. This implies that Scots pine and birch may be at greatest risk to snow-induced damage in the near future (Kellomäki et al. 2005).

Trends and changes in storm winds have been investigated by employing long time series of observed wind speeds, wind speeds based on reanalyzed meteorological datasets (e.g., Uppala et al. 2005; Dee et al. 2011), and climate model simulations. Because wind measurements are dependent on the conditions of the measurement site, the measuring instruments, and the measurement height, a wind speed time series can very seldom be regarded as homogeneous. Therefore, it is difficult to make comprehensive and reliable studies based on in situ data. Thus, it is not surprising that past changes in wind speeds may indicate decreasing or increasing trends, depending on the location. When studying historical trends, reanalysis can be beneficial because it is built on observed weather parameters and numerical weather prediction models. The reanalyzed weather data sets also form a homogenous dataset for wind speeds. The longest meteorological reanalysis to date covers the years 1871-2008 and indicates that storminess has been trending upward in northwestern Europe (Donat et al. 2011a). However, understanding of climate change impacts on winds in Europe is still uncertain (Räisänen et al. 2004; Ruosteenoja et al. 2005; Bärring and Fortuniak 2009; Nikulin et al. 2011; Donat et al. 2011b and references therein).

Many recent analyses project an increase in storm winds in northwestern and eastern Europe, not including Finland. The projected changes are usually rather small. The results are uncertain since many of the investigations have only used a few models or the models have not been independent. To gain more certainty in extreme wind investigations, one should have a large set of data that can be statistically analyzed to obtain information about change and its certainty.

As the climate warms, the duration of the soil frost season is projected to shorten and the soil frost depths to decrease in Finland (Peltola et al. 1999a; Venäläinen et al.

2001a, b; Kellomäki et al. 2010; Gregow et al. 2011). However, sudden short mild and rainy periods during winter may result in an increase in soil frost depths. If the mild and wet period lasts for several days, it is more likely that the frozen soil will melt even in midwinter (Gregow et al. 2011). This indicates that despite changes in windiness, a risk of uprooting of trees, especially of Norway spruce, may increase in the future between late autumn and early spring.

1.3 AIMS OF THE WORK

The main aim of this work was to analyze the potential impacts of occurrence of strong winds, heavy snow loads, and soil frost conditions on the risks to forests in Northern Europe and to test how these may be changing due to ongoing anthropogenic global warming. More specifically the analyses concentrated on:

i) changes in the combined occurrence of strong winds, heavy snow loads, and unfrozen soil conditions in Finland (Paper I);
ii) regional risks to Finnish forests from heavy snow loads (Paper II) and strong winds (Paper III);
iii) the mean and extreme geostrophic wind speeds in Northern Europe, based on nine global climate models (Paper IV); and
iv) estimation of windstorm-related timber losses in Europe in 1960-2011 by using the geostrophic and ageostrophic isallobaric winds as a basis for the analyses (Paper V).

2. MATERIAL AND METHODS

2.1 DESCRIPTION OF THE METEOROLOGICAL DATASETS

Outlines for the datasets used

Various sources of data were used in Papers I-V. Table 1 shows the main meteorological and forest-related data sets that were investigated. The various GCMs employed in Papers I-IV originated from the subset of the 23 models used in the Intergovernmental Panel on Climate Change 4th Assessment Report in 2007 (IPCC 2007).

Table 1. Summary of the main data used in the calculations. T2m (°C) means temperature at 2-meter height above surface, SLP (hPa) is the sea level pressure, V 10min (ms^{-1}) is the 10-minute mean wind speed, Prec (mm) stands for precipitation, primary forest damage means the storm-induced timber losses (Mm^3), and NFI stands for National Forest Inventory data.

Summary of data	Current climate	Observations or reanalyses	Parameters	Forest data	No. of GCMs	Scenario (Fig. 2)	Future climate
Paper I	1971-2000, 1980-2009	FMI archive	T2m, SLP, V 10 min, Prec		10+ 19	A1B	2046-2065, 2081-2100
Paper II	1961-1990	FMI archive	T2m, SLP, V 10 min, Prec	NFI 8	19	A2	1991-2020, 2021-2050, 2070-2099
Paper III	1961-1990	FMI archive	T2m, SLP, V 10 min, Prec	NFI 9	19	A1B	2001-2020. 2021-2050. 2070-2099
Paper IV	1971-2000	ERA-40	T2m, SLP		9	A1B, A2, B1	2046-2065, 2081-2100
Paper V	1960-2002, 1979-2011, 1960-2011	ERA-40, ERA-Interim, EFI-ATLANTIC	T2m, SLP	Primary forest damage			

The model-simulated data were downloaded from the Coupled Model Intergovernmental Project 3 (CMIP3) archive (Meehl et al. 2007). The models used in the analyses were chosen so that their spatial resolution was 300 km or better. The time periods were constructed for the GCMs considering the SRES A1B, A2, and B1 scenarios (Nakićenović et al. 2000) (Fig. 2).

In Papers I-IV, the investigations that were related to the observed weather concentrated on seven locations in Finland: Helsinki, Kauhava, Jyväskylä, Joensuu, Kajaani, Rovaniemi, and Sodankylä (Table 2). In Paper IV the changes in the occurrence of the extreme wind speeds were additionally compared between southern part of the Baltic Sea (55 °N; 15 °E) and eastern Finland (Joensuu) (Paper IV, Table 2).

Table 2. Main locations studied. "OBS station" refers to the coordinates of the measurement site and "Grid point" to the closest nearby grid point of the GCMs.

Location	OBS station	Grid point
Helsinki	60,372 °N ; 24,960 °E	60,0 °N ; 25,0 °E
Joensuu	62,660 °N ; 29,615 °E	62,5 °N ; 30,0 °E
Jyväskylä	62.402 °N ; 25.679 °E	62.5 °N ; 25.0 °E
Kajaani	64,281 °N ; 27,679 °E	65,0 °N ; 27,5 °E
Kauhava	63,120 °N ; 23,047 °E	62,5 °N ; 22,5 °E
Rovaniemi	66,558 °N ; 25,835 °E	65,0 °N ; 25,0 °E
Sodankylä	67,366 °N ; 26,633 °E	67,5 °N ; 25,0 °E

2.2 OUTLINES FOR THE ECOSYSTEM MODEL AND THE MECHANISTIC WIND DAMAGE MODEL USED

The ecosystem model SIMA (Papers II and III)

The ecosystem model SIMA (Kellomäki et al. 1992a) was employed in Papers II and III to simulate the growth and dynamics of managed forests based on the Finnish national forest inventory (NFI 8 and 9) data throughout Finland with implications for timber production and the snow- and wind-induced risks to forests. In the SIMA model, the dynamics of tree stand are determined by the number and mass (including foliage, branches, stem, and roots) of trees. The diameter growth of each tree is limited by the temperature sum (degree days), within-stand light conditions, soil moisture, soil nitrogen availability, and atmospheric CO_2 level, which all have a direct effect on birth and growth and an indirect effect on the death of trees (Kellomäki et al. 1992a, b, 2005, 2008). The management applied in model simulations included regeneration, thinning, and final cut, following the recommendations for forest management in Finland (see details in Papers II and III). However, the proportions of tree species were not controlled in management (see details in Paper III).

A description of the SIMA model with inputs needed and its validation have been presented in detail previously, for example, by Kellomäki et al. (1992a, 2005, 2008), Kellomäki and Kolström (1994), and Kolström (1998), and are also discussed in Papers II and III. Based on the earlier findings, the SIMA model is expected to simulate the volume growth of managed stands with good agreement with i) the measured values of volume growth on the permanent sample plots of the National Forest Inventory throughout Finland, and ii) the statistical growth and yield model MOTTI of the Finnish Forest Research Institute (see Kellomäki et al. 1992a, b; Kolström 1998; Talkkari et al. 1999; Routa et al. 2011a, b, 2012). The model is parameterized for the main tree species such as Scots pine, Norway spruce, and silver and downy birch between latitudes N 60° and N 70° and longitudes E 20° and E 32° within Finland (Kellomäki et al. 1992a, b; Kolström 1998). The SIMA-model is run on an annual basis, and the computations are based on an area of 100 square meters.

The mechanistic wind damage model HWIND (Paper III)

The mechanistic wind damage model HWIND (Peltola et al. 1999a) was used in Paper III to estimate the critical wind speed needed to uproot trees (a 10-minute average wind speed at 10 m height above ground). The effects of climate change on the risk of wind-induced damage was analyzed based on average critical wind speeds calculated for uprooting trees on forest inventory plots, percentages of forest area in each critical wind speed class (<14, 14-17, 17-20, >20 m s^{-1}), and concurrent probabilities of such wind speeds to occur in each regional unit of the Forest Centre of Finland (13 Finnish forest centers were merged in 2012). The limits for these wind speed classes were built based on the fact that in Finland over the sea areas, wind speeds $\geq$ 14 m s^{-1} are classified as strong winds and winds $\geq$ 21 m s^{-1} as storms. When the 10-minute mean wind speed is $\geq$ 21 m s^{-1} over the sea areas, the risk for stormy wind gusts on land is assumed to be likely. Still, mean wind speeds $\geq$ 21 m s^{-1} on land areas occur only in Lapland, where there are hills and canyons and the surface roughness is smaller. In the forested areas in Finland, the critical wind speeds 11-17 m s^{-1} in particular have caused uprooting or stem breakage in tree stands in unfrozen soil conditions in summer and autumn.

The critical wind speeds were calculated annually (2001-2100) for each forest inventory plot having height $\geq$ 10 m. When considering the risks of wind-induced damage in simulations for either summer or autumn, the soil was presumed to be unfrozen. Furthermore, birches were expected to have no risk in autumn without leaves, the opposite of summer with leaves. The tree stands with the average height < 10 m were classified as no-risk stands, similar to birch without leaves.

The HWIND model assumes that a tree is uprooted if the applied bending moment (due to forces by wind and gravity) of a tree exceeds the maximum resistive moment of the root anchorage. Stem breakage is assumed to take place if the breaking stress exceeds the critical value of the modulus of rupture (Petty and Worrel 1981; Peltola et al. 1999a). The HWIND model requires as inputs the tree species, average tree height and diameter at breast height (DBH), stand density (i.e., SIMA outputs), distance from the upwind forest edge, and upwind gap size (in terms of perimeter length in tree heights).

The properties and details of the HWIND model and the validity of its predictions for Finnish and Swedish conditions have been discussed in detail previously by Peltola et al. (1999b), Gardiner et al. (2000), Talkkari et al. (2000), Blennow and Sallnäss (2004), and Zeng et al. (2004, 2006, 2007), for example. Based on earlier validation work carried out for HWIND, and comparison against corresponding predictions by other mechanistic models (e.g., ForestGales and FOREOLE; see Gardiner et al. 2000, 2008; Ancelin et al. 2004), it is expected that the predicted critical wind speeds of this work will provide results with an accuracy typical for these kinds of models. Zeng et al. (2006) have also previously evaluated in detail the validity of the integrated use of SIMA and HWIND simulations and how possible errors of any input data (for SIMA and/or HWIND) may propagate and affect the accuracy of risk assessment. Based on these previous studies, it is expected that the integrated use of SIMA and HWIND model simulations will provide useful results for risk assessment.

2.3 CALCULATION OF WEATHER RISKS TO FORESTS

Winds (Papers I, III-V)

The observed wind speeds were translated to a common 10-meter height according to the logarithmic wind profile (Paper I, Eq. 1). The roughness values describing the site vegetation were adopted from Tammelin (1991). In Papers I, IV, and V, the geostrophic wind speeds (e.g., Holton, 1992) (see schematics in Fig. 3) of the GCMs and reanalyses were used instead of the parameterized surface wind speeds because the surface pressure gradients and therefore the geostrophic winds (Paper I, Eq. 2, and Paper IV, Eq. 1) are more comparable between the models than the parameterized surface (true) winds.

The geostrophic wind speed describes the speed of air flowing without any influence of surface friction. It is calculated from the pressure difference, also taking into account the surface temperature and rotation of the Earth (Coriolis force). The observation based data ERA-40 (Uppala et al. 2005) were applied for evaluation of the GCM data when the suitability of the GCMs for geostrophic wind speed analyses was assessed.

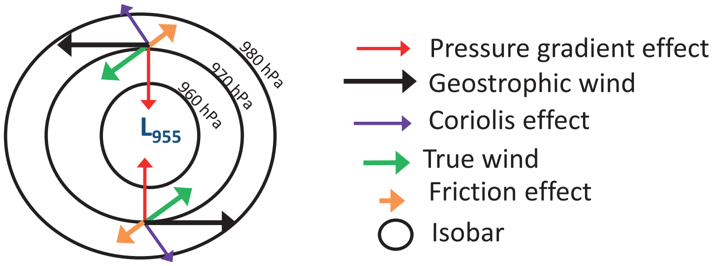

Fig. 3. Schematics of winds around a storm center marked with L_{955} *(955 hPa deep).*

The daily GCM geostrophic wind speeds were also translated to correspond to the wind speeds at 10-meter height (Paper I, Eq. 3) by applying the method of Cressman (1960) with some modifications. The daily average of these modified wind speeds and a daily average of temperature and precipitation of 19 GCMs were employed in the snow load (Paper I, Eqs. 4-6) and uprooting/stem breakage risk calculations in Paper I.

In Paper V, ageostrophic isallobaric wind speeds (Fig. 4) were also calculated. These describe the effect of the movement of the whole low-pressure area on storm winds. In the northern hemisphere, ageostrophic isallobaric wind speeds increase the mean wind flow on the right-hand side of the low pressure center in regard to the direction of propagation and decrease the wind speeds on the left-hand side (e.g., Lim et al. 1991 and references therein). The impacts of intense, rapidly moving storms are better localized in the analyses when ageostrophic isallobaric wind speed is included in the calculations.

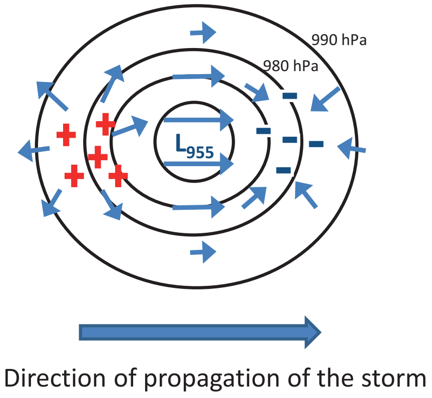

Fig. 4. Schematics of the ageostrophic isallobaric wind field. The plusses indicate rapid pressure rises and the minuses rapid pressure drops.

Soil frost depth (Papers I, III)

Soil frost depths (Paper I, Eq. 7) were calculated according to an approach used by Venäläinen et al. (2001b), in which they assumed that the ground is free of snow. This method is based on the negative of the sum of the daily average temperature from October 1 to when the frost sum accumulation ends in the spring. The soil properties are described by two parameters. The largest value for the sum of the cumulative daily temperature was limited to 10°C to avoid unrealistic values.

The snow-free soil frost depth was classified into the following categories: 1) 0–20 cm, 2) 20–40 cm, 3) 40–60 cm, and 4) >60 cm (Papers I and III). These classes correspond to about double of that of actual forest soil (see Paper I). Therefore, soil frost categories 1–3 represent a risk of trees for uprooting, in line with previous work by Peltola et al. (1999a). Class 4 provided sufficient support for the anchorage of trees, but includes a risk for stem breakage if there was concurrent heavy snow and wind loading (Paper I, Table 6).

Snow loads (Papers I and III)

Snow accumulation was considered to be continuous. Cumulative precipitation and the wearing effects of air temperature and wind speed were used in the snow-load calculation as input variables. The loss of snow load by melting (%) was calculated by assuming that melting starts when the 2m air temperature *(T)* is higher than 0°C and that also snow has melted when the temperature reaches 2.3°C. Loss of snow load by wind removal (%) was calculated by assuming that when the 10-minute average wind speed *U* increases to 10 m s^{-1}, 20% of the snow will fall from the tree (stem and branches) during the next 3 hours (Gregow et al. 2008), and when U reaches approximately 16 ms^{-1}, all the snow is removed. In this model, unlike in the models of Li and Pomeroy (1997), the wearing of wind starts directly if there is any wind. In addition, the increase in snow load by precipitation was calculated so that precipitation measured in mm per time step at each station was directly converted to mass per unit area (kg m^{-2}). The snow loading was, therefore, calculated for every time step. The snow loads of at least 20 kg m^{-2} (i.e., equivalent for 20 mm of precipitation) were analysed as representing a risk to forests (Papers I-II).

Storm severity, timber losses, and impact of spatial and temporal resolution on the analyses (Paper V)

In Paper V, the main aim was to test the possibility of assessing the losses of timber due to storm winds by employing the ERA-40 and ERA-Interim datasets and different temporal and spatial resolutions. The ERA-40 spatial resolution is 1.125° and that of ERA-Interim is roughly 0.7°. Fifty-four storms that had caused at least 2 Mm^3 primary damage to forests in Europe in 1960-2011 were chosen for closer analyses from Finland and the EFIATLANTIC storm catalogue. The regression analyses were performed using the sum of the geostrophic and ageostrophic isallobaric wind speeds.

The sum of the geostrophic and ageostrophic isallobaric wind speed was named “SWIND.” The timber loss estimate (TILT) was calculated based on the rule that the highest storm wind speed SWIND has to occur at two time steps on the path of the storm on land (duration criteria 6-12 hours):

$$TILT = \begin{cases} < 2Mm^3, \quad SWIND < 40, \\ (0.0003 \times SWIND^3 + 0.0599 \times SWIND^2 \text{ - } 1.8532 \times SWIND)Mm^3, \\ when \quad 40 \leq SWIND < 110 \quad and \\ = 120Mm^3, \quad SWIND \geq 110 \end{cases}$$

(1)

For the current climate, an approach (TILES) that takes into account the spatial extent of the storm over land was estimated. Each country was assessed separately, and the highest SWIND on forested areas on land was used in the equation:

$$TILES = 0.018Mm^3 \times SWIND_{MAX}(ms^{-1})/(ms^{-1}) \times AREA(ha)/10^6\,ha \qquad \textbf{(2)}$$

The size of the areas with SWIND above 40 ms^{-1} were estimated for 11 of the well-known storms, i.e., storms on 17.10.1967, 22.9.1969, 29.9.1969, 1.11.1969, “Janika”, and “Mauri”, in addition to storms causing moderate to extreme damage when moving (mostly) over forested regions, such as “Lothar”, “Martin”, “Per”, and “Gudrun”. These storms formed the basis for testing the regressions.

2.4 APPLIED EXTREME VALUE ANALYSING TECHNIQUES

The Generalized Extreme Value (GEV) theory (Coles 2001; Castillo et al. 2004) was used when the return periods of the calculated maximum wind speeds and snow loads were assessed (Papers I, III, and IV). In this context, the Extremes Toolkit software package, developed by the National Center for Atmospheric Research (NCAR) (e.g., Katz et al. 2005), was employed. The maximum annual snow loads and maximum annual geostrophic winds speeds during the windy season (September 1-April 30) were analysed using the block maxima method (Papers I and IV) and the peak over threshold method (POT) (Paper III). According to Naess and Clause (2000), the POT method is a good alternative to the block maxima method for estimating extreme values when the return periods are much longer than the periods of data acquisition. For optimization purposes, the Nelder-Mead-method was applied in Paper III. In Papers I and IV, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method (Broyden 1970; Fletcher 1970; Goldfarb 1970; Shanno 1970) was used instead.

To provide a larger dataset of wind speeds for estimating the return periods (*RP*) of 5, 10, 50, and 100 years, future projections of the GCMs (see Paper IV, Table 2) for the various scenarios were combined (A2:A1B:B1). The changes were also estimated by employing the scenarios separately to gain understanding of the uncertainty related to the choice of scenarios and GCMs. The calculations were performed using the whole gridded dataset and a new simplified method (Paper IV, section 2.4.2).

3. RESULTS

3.1 STRONG WINDS, SNOW LOADS, AND SOIL FROST UNDER THE CURRENT AND CHANGING CLIMATE (PAPERS I-IV)

The future projections made using 9 GCMs (Paper IV) indicate that mean and extreme wind speeds are projected to increase by 2-4% in the southern and eastern parts of Northern Europe and decrease by 2-5% over the Norwegian Sea by the end of this century (Paper IV, Fig. 3 and Figs. 5-7). The result is statistically significant at the 95% level. The smallest change is projected under the B1 and the largest under the A1B and A2 scenarios (Fig. 2). The changes in wind speeds projected for Finland show that by 2046-65, there are nearly no changes, but by 2081-2100, the increase is seen, especially in northern Finland (Paper IV, Figs. 5-7). An example of the changes that are projected to occur by 2081-2100 in southern Finland (Helsinki) is depicted in Fig. 5.

Under the current climate, the return levels of wind speeds occurring once every 10 years correspond to maximum 10-minute wind speeds of 17-18 m s^{-1} (Papers I, III-IV) in the southern and western parts of the country (Helsinki, Kauhava, and Rovaniemi). In the east (Joensuu) and further north (Sodankylä), the corresponding wind speed is 14 m s^{-1}. Based on Paper IV, the wind speeds that occur during September-April once in 10 or 50 years appear to be approximately 13% ± 2% and 22% ± 5% stronger than the 30-year averages.

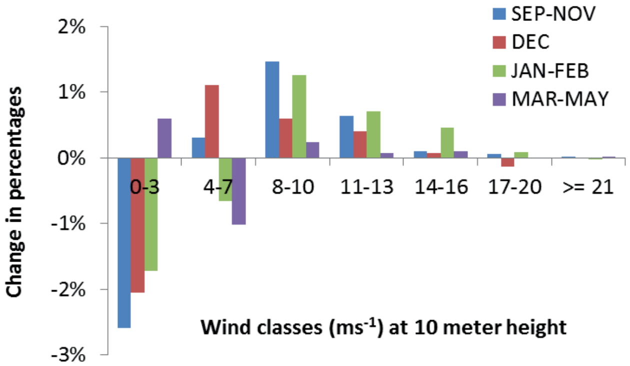

Fig. 5. The projected changes of the daily mean wind speeds of 10 GCMs in September-May from 1971-2000 to 2081-2100 at grid point 60°N, 25°E that represents Helsinki (drawn based on the data of Paper I).

Based on the observed wind speeds ≥ 8 m s^{-1} in 1971-2000 in September-May in Lapland (Rovaniemi, Sodankylä) and southern coastal Finland (Helsinki), the main wind direction is also from the south or southwest (Paper I, Fig. 4). Altogether, 50-56% of the winds blow from these directions. In the western coastal zone (Kauhava), the corresponding winds main blow from southwest, south, and southeast. In the central part of Finland, westerly to northwesterly and southerly winds dominate.

The 10-year return level averages of snow loads vary under the current climate between 23 kg m^{-2} (Helsinki, Kauhava) and 31-33 kg m^{-2} (Joensuu, Sodankylä), respectively. Independent of the snow load amount, the observed wind speeds are mostly below 8 ms^{-1} (Paper I, Fig. 8). Concurrent heavy snow loads and low soil frost depths (< 60 cm in snow-free road conditions, corresponding <30 cm in forest soil) typically occur in northern and eastern Finland.

The future projections of the occurrence of days having snow damage risk show a decline from the current climatic conditions toward the end of this century. Averaged over the whole country (Paper II, Fig. 2), the mean number of days with snow loads>20 kg m^{-2} per year will, in general, decrease by 11%, 23%, and 56% in 1991-2020, 2020-2050, and 2070-2099, compared to the baseline period, 1961-1990. In Paper III, the overall decline in the occurrence of snow loading regardless of its amount, assuming the SRES scenario A1B, varied from 5% (north) to 50% (south) until 2100 (paper I, Table 4). This was caused especially by the decrease in the lighter snow loads < 20 kg m^{-2} (paper I, Table 5). Nevertheless, the occurrence of snow loads above 20 kg m^{-2} (heavy ones) showed an increase by 22-45% in Helsinki, Joensuu, and Rovaniemi from the current 1971-2000 toward 2046-2065. This means that in the near future, although there will be fewer days with heavy snow loads, the snow loads during the days when it snows much may be larger than under the current climate.

A comparison between the soil frost depths in 1971-2000 and 1980-2009 shows that the soil frost depth in autumn (by December) has already decreased by 5-10% in southern and central Finland, while in the north, the change is not so clear (paper I, Fig. 5). Toward the end of this century, the soil frost depths and their support to the anchorage of trees will decrease, especially in southern and central Finland (paper I, Fig. 9). In the north, the annual duration of the soil frost in class 4, corresponding approximately to >60 cm on snow-free ground (30 cm of actual forest soil), will decrease on average by 50 days and, thus, by 25%. In the east, the corresponding decreases are 100 days and 75%, respectively.

The projected changes in the concurrent occurrence of strong winds, heavy snow loads, and soil frost depths indicate that the risks for conditions favorable for either uprooting or stem breakage in the forests are increasing (paper I, Table 6). The conditions making trees liable to uprooting (i.e., decreased soil frost, heavy snow loads, strong winds) increase at least in southern, central, and eastern Finland. The risks for conditions favorable for stem breakage increase in northern Finland.

3.2 WEATHER RISKS IN MANAGED FORESTS IN FINLAND (PAPERS I-III)

Regarding wind-induced risks to forests, the differences under the current and changing climate in percentages of areas in each regional unit of Forest Centre were very small in different critical wind speed classes in the first period (2001-2020) (Paper III, Fig. 6). In general, the most southern regional units (1-4) had the highest share (ranging between 23% and 47%) of forest area exposed to wind risk (critical wind speed $< 17 \text{ m s}^{-1}$) in autumn. In the second and third periods, the corresponding shares of forest areas at risk in these regional units decreased. In other parts of Finland and especially in northern Finland, the risk was low regardless of the period or climate scenario applied. These drastic changes in southern-most Finland, when the proportions of tree species in forest stands were not actively controlled, are due to the decrease of the dominance of Norway spruce and concurrent increase in birch, especially in southern Finland. Norway spruce needs approximately 20% lower critical wind speeds in HWIND simulations compared to Scots pine and birch (in leaf) of similar size. However, in autumn, birch was also expected to be leafless and not suffer wind damage, unlike during summer, which also can be seen from these results.

The temporal and spatial variability of the risk of snow-induced damage (with snow loading>20 kg m^{-2}) to forests is also affected by changes of the growing stock (Papers II, III) under the changing climate. The highest mean amount of annual growing stock at risk was found in central Finland, northern parts of Kainuu and Pohjois-Pohjanmaa, and in northwestern Finland in the second 30-year period (Paper II, Fig. 5). Until the end of this century, the amount of growing stock at risk, however, decreased in the majority of the country (Paper II, Fig. 5).

3.3 POSSIBILITIES IN ASSESSING TIMBER LOSSES DUE TO STORMS (PAPER V)

In Paper V, the sum of the geostrophic and ageostrophic isallobaric wind speeds correlated with the reported losses of timber in forests due to storms. An example of how well the regression equations TILT and TILES can estimate timber losses is depicted for five storms in Fig. 6.

The 54 European storms (1961-2010) were divided into 5 categories based on the primary damage to forests : 1) minor storms causing minor damage, 2-10 Mm^3; 2) moderate storms causing moderate damage, 11-30 Mm^3; 3) severe storms causing high damage, 31-70 Mm^3; 4) very severe storms causing very high damage, 71-110 Mm^3; and 5) extreme storms causing extreme damage,>110 Mm^3. These classes correspond to maximum wind gust estimates of 1) 31-32 ms^{-1}, 2) 33-36 ms^{-1}, 3) 36-40 ms^{-1}, 4) 41-46 ms^{-1}, and 5) ≥ 47 ms^{-1}. Finnish storms belong to class minor because they have only caused timber losses of 2-10 Mm^3 in magnitude. The worst storms influencing Sweden have been moderate, severe, or very severe (Alexandersson 2005; Skogsstyrelsen 2006; Bengtsson and Nilsson 2007; Valinger and Fridman 2011).

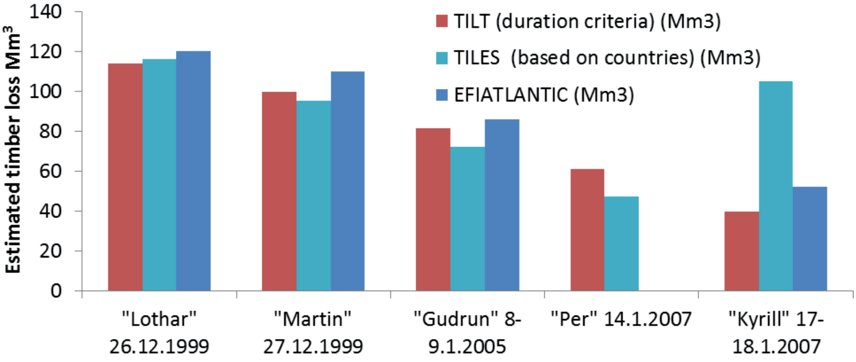

Fig. 6. Comparison of regression-based estimates for timber losses given by TILT and TILES (Eq. 1 and 2) for five well-known storms from Paper V. The total primary damage losses of storm "Per" are incomplete in the EFIATLANTIC.

TILT appears to be suitable for describing the severity of rapidly moving large scale storms. TILES can be used for estimating regional damages, but it has a tendency to overestimate the volume of primary damage. The primary damage recorded of storm Kyrill (Pinto 2009; Fink et al. 2009) in the EFIATLANTIC storm catalogue is around 52 Mm^3, and it is the sum of primary damage reported from Germany, Poland, and Czech Republic. Reports from other affected countries are not presented. Still, the estimate 110 Mm^3 (Fig. 6) based on TILES appears to be too large.

Based on TILT (Fig. 6), the storm “Gudrun” could have damaged 70-80 Mm^3 of timber over the whole domain it influenced. However, based on TILES, the loss of timber in Sweden would have been only 24 Mm^3 (Paper V, Table 4). For storm “Per”, the losses based on TILES were estimated at around 18 Mm^3 in southern Sweden, whereas the real loss was 12 Mm^3. For storms “Lothar” and “Martin”, the TILT and TILES give rather similar numbers for primary damage. The known overall damage due to these storms was around 230 Mm^3 based on the EFIATLANTIC storm catalogue.

In addition to the damage analyses, Paper V demonstrated that the temporal and spatial resolution of the meteorological data received either from the reanalyzed data or from the climate model is important in the storm impact analyses. By using too low a temporal resolution, the storm risk signal may be shifted hundreds of kilometers along the path of the storm. By using too low a spatial resolution, the wind speeds decrease, but the signal location is still approximately the same as when using higher spatial resolution.

4. DISCUSSION AND CONCLUSIONS

4.1 EVALUATION OF THE APPROACHES AND RESULTS

The most reliable results in climate research are based on large model ensembles. It is clear that the results of the average changes and uncertainties presented in Papers I-IV are a good starting point for risk analyses. However, rather than utilizing only ensembles and then making ensemble mean projections it is also good to look at the changes model by model and then form the projections. By doing so, uncertainty analyses can also be made. This was done in Paper IV with geostrophic winds.

The snow load model succeeded in giving a rather realistic picture of the spatial and temporal differences in the snow loads (Papers I-III). However, in future work and further development of this snow load model, it would be essential to consider aspects such as i) the effect of drifting snow (e.g., Degaetano and O'Rourke 2003), ii) the impact of humidity that can cause ice loadings or otherwise make the snow heavier, iii) the effect of ageing of snow (Yong and Metaxas 1985), iv) the effect of snow pack properties on starting point for snow loss (Li and Pomeroy 1997), and v) swaying of trees (Peltola et al. 1996).

In this work, the soil frost depths were simulated for snow-free ground (road soil) applying the previous work of Venäläinen et al. (2001b). As a result, the frost depths simulated corresponded to approximately double the corresponding soil frost depths of the actual forest soils measured by the Finnish Environmental Institute. A further development of this approach could be to utilize, in addition to temperature and soil properties, changes in snow cover caused by rainfall as well as melting and freezing (Gregow et al. 2011). Such a set of variables could still be used to analyze when employing the GCM or the RCM data.

The dynamics of forest stands were simulated in this work by the ecosystem model SIMA. The average results for tree and stand characteristics of the SIMA simulations were further used as an input in the mechanistic wind damage model HWIND. Based on earlier findings, the SIMA model is expected to simulate the volume growth of managed stands in good agreement with the measured volume growth on the permanent sample plots of the National Forest Inventory throughout Finland and the statistical growth and yield model MOTTI in main tree species. Earlier critical wind speed predictions of the HWIND model have also been in line with corresponding predictions of other mechanistic models (e.g., ForestGales and FOREOLE). However, any inaccuracies in the input of tree characteristics for HWIND and parameters that control the magnitude of wind loading or resistive bending moments of trees can have significantly affect the predicted critical wind speeds for uprooting and stem breakage (see Peltola et al. 1999b). Thus, errors of input data used for the SIMA model (e.g., DBH) may propagate (e.g., effects on height) and affect the accuracy of the wind damage assessment in terms of the classification of stands (height ≥10 m) in stands with a possible risk of damage by the integrated models (see, e.g., Talkkari et al. 2000; Blennow and Sallnäs 2004; Zeng et al. 2004, 2006, 2007). However, based on the earlier validation work for these component models (SIMA, HWIND), it is expected that the simulations of this work provide results with an accuracy typical for these kinds of models.

The regression-based timber loss estimates TILT and TILES (Paper V) gave rather similar results for the primary timber losses due to strong winds when considering the whole area influenced by the storm. Using TILES is practical when country-specific primary losses are assessed. However, these methods could still be developed further by including information about tree volumes as well as tree species distribution in forests.

Projected changes in the potential risks for wind- and snow-induced damage

The projections concerning the occurrence of different wind speeds show that there will be rather small changes in windiness during this century (Papers III-IV). The increase in mean and extreme geostrophic wind speeds by 2-4% in the southern and eastern parts of Northern Europe, including Finland, and the decrease by 2-5% over the Norwegian Sea is, nonetheless, statistically significant at the 95% level. Qualitatively similar trends have been found in the investigations of Bengtsson et al. (2006, 2009) and Nikulin et al. (2011). By employing six GCMs, Nikulin et al. (2011) showed that wind speeds will increase in the Baltic Sea region, southern and eastern Finland, and the northwestern part of Russia.

The individual GCMs in Paper IV as well as in the work of Nikulin et al. (2011) indicate that depending on the model, the impact is shifted more or less over Finland.

In Nikulin et al. (2011), the gust wind speeds occurring once in 20 years differ quite a bit between the models. Three of the models indicate up to 10-20% increase in wind gusts over Finland, whereas two of the models indicate almost no change and one model shows a similar decrease. Also, the individual 9 GCMs employed in Paper IV showed both local increases and decreases. In addition to the differences in the results between the GCM-based damage analyses, Paper V demonstrated that the temporal and spatial resolution of the meteorological model is important and may affect the results. For instance, when the temporal resolution is low, the storm risk signal may be located hundreds of kilometers away from the real risk area. Additionally, the low spatial resolution in the calculations decreases the wind speeds and, therefore the extremes are not captured properly. However, using low spatial resolution with high temporal resolution places the high wind speeds of the storms nearly as well as when using both high spatial and temporal resolution.

Future projections of snow damage risk show a decline from the current climatic conditions. Averaged over the whole country (Paper II, Fig. 2), the mean number of days with snow loads>20 kg m^{-2} per year will, in general, decrease by 11%, 23%, and 56% in the 1991-2020, 2020-2050, and 2070-2099 periods, respectively, compared to the baseline period 1961-1990. However, in Paper III, the occurrence of heavier snow loads of >20 kg m^{-2} showed an increase by 22-45% in the Helsinki, Joensuu, and Rovaniemi regions around 2046-2065. This kind of a possibility for a temporal increase in heavy snow loads was assumed in Paper I as well. Also Carter et al. (2005) and Räisänen (2008) have found that climate warming will at first result in larger daily snowfall amounts.

Toward the end of this century, the deeper soil frost classes (e.g., road, snow-free, soil frost>60 cm, corresponding >30 cm depth in forest soil) will nearly disappear in southern and central Finland (Paper I, Fig. 9), decreasing also the anchorage of trees from late autumn to early spring, i.e., during the windiest season of the year. In 2046-2065, some winters can already lack sufficient soil frost depths, which support tree anchorage. In 2081-2100, this could be happening annually throughout southern and central Finland and possibly even in eastern Finland. Peltola et al. (1999b) and Kellomäki et al. (2010) showed the same kinds of results.

Projected risks to forests due to the changes in forest dynamics

In Paper III, it was shown that in some of the most southern regional units of Forest Center of Finland, the dominance of Norway spruce (with shallow rooting) is projected to decrease under the changing climate toward 2100, which is the opposite of birches, but also true of Scots pine. This result was partly due to the fact that under the changing climate, Norway spruce is the most susceptible to drought risk, which increased its mortality in model simulations, too. However, tree species proportions were not actively controlled by thinning, which affected the success of birch in particular. Since Norway spruce with its shallow anchorage is the most vulnerable tree species to uprooting in Finnish conditions, the risk of wind damage could theoretically to some extent be prohibited in autumn (and winter) when birch without leaves does not suffer damage. On the other hand, decrease in soil frost from late autumn to early spring will concurrently increase the risk of damage, especially in Norway spruce and Scots pine. But in summer, when birch is in leaf, the risk will be considerable, regardless of tree species. This will be particularly so if severe weather events such as were experienced after the record warm summer of 2010 in Finland occur more often in the future. Furthermore, projected increases in both stocking (Paper III) and extreme winds (Paper IV, Figs. 5-7) may change wind-induced risks to forests.

The highest risk for snow-induced damage to forests will be in central Finland, northern parts of Kainuu, Pohjois-Pohjanmaa, and northwestern Finland by the middle of this century (Paper II, Fig. 5). The risk for snow damage will be highest in young and medium age stands in Scots pine and birch, as has also been shown in previous studies (Valinger et al. 1993; Valinger and Lundqvist 1994). In these parts of Finland, the snow loads were also found to have the highest return levels of 31-33 kg m^{-2} once in 10 years under the current climate in Papers I and II.

4.2 CONCLUSIONS

Under the current climate, large-scale storms that have caused significant forest damage have typically approached Northern Europe from the Atlantic. The main storm tracks have been directed over southern and central Scandinavia toward Finland, Russia, and the Baltic countries (Paper V, Fig. 1). The strongest storms tend to appear over the Northern Atlantic and near the coasts.

The risk for uprooting and stem breakage of trees in the managed Finnish forests is caused by combinations of strong winds, heavy snow loads, and unfrozen soil (Papers I-III). The concurrent increase in the occurrence of strong winds and heavy snow loads under unfrozen soil conditions indicate that the risk for uprooting may increase significantly in southern, central, and even eastern Finland in the next few decades. In the north, climatic conditions favorable for snow-induced damage show an increasing trend, too. These threats should be taken into account in forest management, if possible, especially in the riskiest areas. The decrease of soil frost with the projected increase in liquid precipitation will also negatively affect the carrying capacity of forest soils from late autumn to early spring and thus implementation of forest harvesting operations, too.

Overall, the results of this work provide valuable information for the Finnish forestry. However, one should keep in mind that estimating future changes is always challenging because the different global climate models (GCM) and climate change scenarios provide very different projections, and the uncertainties increase the farther out the projections are extended. Furthermore, in addition to climate, forest structure and management also affect future risks to forests (see Kellomäki et al. 2005, 2008).

These factors should be kept in mind when trying to generalize the findings of this work.

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