ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
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133
CONTRIBUTIONS

PROJECTED CLIMATE CHANGE IMPACT ON FIRE RISK AND HEAVY SNOW LOADS IN THE FINNISH FORESTS

ILARI LEHTONEN

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No. 133

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Author
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Title
Projected climate change impact on fire risk and heavy snow loads in the Finnish forests

Abstract
The aim of this work was to study the climate change impact on two specific abiotic risks affecting forests in Finland: fires and heavy snow loads. Approximately 1000 forest fires occur annually in Finland, but thanks to effective fire suppression, the average size of fires is only about 0.5 ha. Occasionally, heavy snow loading causes forest damage, which reduces stand quality in boreal forests experiencing cold winters. In Finnish forests, snow damage occurs most commonly in the eastern and northern parts of the country.

The basic tools used in this work to evaluate the climate change impact were climate models. In addition, observational weather data and fire statistics were used. In evaluating the forest fire risk, the Canadian Fire Weather Index (FWI) system was used. Snow load amounts were estimated mainly by applying a snow load model developed at the Finnish Meteorological Institute (FMI).

The results indicate that forest fire risk will most likely increase in the future due to increasing temperature and enhanced evaporation. However, there is large uncertainty regarding the rate of change, which originates from the differences between climate model responses to the same radiative forcing. Moreover, an increase in forest fire risk will at the same time increase the risk of conflagrations.

Crown snow loads were projected to become heavier in northern Finland and in the regions of Kainuu and North Karelia next to the Russian border. In southern and western Finland the risk of snow damage is expected to decrease. The largest decrease in the risk is projected to occur in coastal areas. In the areas expected to experience increased risk of snow damage, conditions favouring both heavy wet snow loading and rime accretion were predicted to become more common.

The results of this work can be utilized when considering climatically-driven risks in forest management.

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Tekijä
Ilari Lehtonen

Nimeke
Ilmastonmuutoksen vaikutus Suomen metsien paloriskiin ja raskaisiin lumikuormiin

Tiivistelmä
Tämän työn tavoitteena oli tutkia ilmastonmuutoksen vaikutusta kahteen metsiä uhkaavaan abioottiseen riskiin Suomen oloissa: metsäpaloihin ja raskaisiin lumikuormiin. Metsäpaloja Suomessa esiintyy vuosittain noin 1000, mutta tehokkaan palojen torjunnan ansiosta yksittäisissä paloissa keskimääräinen paloala on vain noin 0.5 ha. Lumi aiheuttaa ajoittain metsikön arvoa alentavia tuhoja boreaalisissa metsissä. Suomessa lumituhoja sattuu useimmin maan itä- ja pohjoisosien metsissä.

Ilmastonmuutoksen vaikutuksen arvioinnissa hyödynnettiin ilmastomallien tuloksia. Lisäksi työssä käytettiin säähavaintoaineistoja ja tilastoja metsäpaloista. Metsäpaloriskin arvioinnissa käytettiin Kanadassa kehitettyä FWI-indeksiä (Fire Weather Index). Lumikuormien arvioimisessa sovellettiin puolestaan Ilmatieteen laitoksella kehitettyä ja operatiivisesti käytössä olevaa lumikuormamallia.

Tulosten perusteella metsäpaloriski tulee tulevaisuudessa todennäköisimmin kasvamaan kohonneiden lämpötilojen voimistaman haihdunnan takia. Muutoksen voimakkuudessa on kuitenkin suurta epävarmuutta. Tämä johtuu siitä, että eri ilmastomallien tulokset poikkeavat toisistaan samallakin säteilypakotteella. Joka tapauksessa kasvava metsäpaloriski lisää myös suurpalojen todennäköisyyttä.

Puiden lumikuormien ennakoitiin kasvavan Pohjois-Suomessa sekä Kainuun ja Pohjois-Karjalan maakunnissa. Etelä- ja Länsi-Suomessa lumituhojen riskin ennakoidaan pienenevän, eniten rannikkoseuduilla. Alueilla, joilla lumituhojen riski näyttäisi kasvavan, otollisten olosuhteiden sekä märän lumen että huurretykyn kertymiselle ennakoitiin yleistyvän.

Tämän väitöskirjatyön tuloksia voidaan hyödyntää metsänhoidossa ilmastollisten riskien huomioonottamisessa.

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Preface

This thesis would not have been possible without the help of several people. First, I would like to thank my former boss Dr Hilppa Gregow for her encouragement towards postgraduate studies and for giving me the opportunity to work with this topic. Without these I would probably never have found myself as a postgraduate student.

Secondly, I need to thank Dr Kimmo Ruosteenoja who was the supervisor of my master's thesis. He was the one who familiarized me with the process and joy of scientific writing during this time and when writing my first peer-reviewed scientific paper, although the particular paper is not included in this thesis.

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Helsinki, May 2017

Ilari Lehtonen

Contents

List of the original publications

This thesis summarizes the four research articles listed here. After an overall introduction to the topic, the original papers are reproduced in the end of the thesis with the kind permission of the journals. In the text, the papers are referred to by the Roman numerals I–IV.

I Lehtonen, I., K. Ruosteenoja, A. Venäläinen and H. Gregow (2014). The projected 21st century forest fire risk in Finland under different greenhouse gas scenarios. *Boreal Environment Research*, **19**: 127–139.

II Lehtonen, I., A. Venäläinen, M. Kämäräinen, H. Peltola and H. Gregow (2016). Risk of large-scale fires in boreal forests of Finland under changing climate. *Natural Hazards and Earth System Sciences*, **16**: 239–253.

III Lehtonen, I., P. Hoppula, P. Pirinen and H. Gregow (2014). Modelling crown snow loads in Finland: a comparison of two methods. *Silva Fennica*, **48**: article id 1120.

IV Lehtonen, I., M. Kämäräinen, H. Gregow, A. Venäläinen and H. Peltola (2016). Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change. *Natural Hazards and Earth System Sciences*, **16**: 2259–2271.

1. Introduction

Finland is the most forested country in Europe (Fig. 1) with forest land covering 76% of the Finnish territory, corresponding to about 23 million ha (Finnish Forest Research Institute, 2011). Financial and spiritual development in Finland has been linked to forests for centuries, and forests are the most important natural resource in the country (Finnish Forest Research Institute, 2011). Moreover, Finland is financially more dependent on forests and the forest industry than any other country in the world (Finnish Forest Research Institute, 2011). In countries like Finland, forest-based bioeconomy has a key role in climate change mitigation efforts (Ministry of Employment and the Economy et al., 2014). Efficient mitigation requires increasing carbon sequestration and use of forest biomass to substitute for fossil-intensive fuels, materials and products (Kilpeläinen et al., 2016). This emphasizes the importance of understanding the risks affecting the forests under changing climatic conditions.

Various abiotic and biotic agents cause damage in forests. Biotic factors are any living components that affect the environment, whereas abiotic factors are non-living parts of the environment that affect the functioning of ecosystems. According to the 10th National Forest Inventory conducted during 2004–2008, about 25% of the forest land in Finland suffered from damage which reduced stand quality (Finnish Forest Research Institute, 2014). Forest damage is somewhat more common in northern than southern Finland. In particular, abiotic factors cause more damage in the northern parts of the country: 12.1% of the forest land in northern Finland reportedly suffered from damage of abiotic origin but only 3.4% in southern Finland.

Abiotic stress factors affecting the Finnish forests include, for example, windstorms, snow, fire and floods. This work focuses on snow and fire damage, although wind is clearly the most important abiotic agent causing damage in Finnish forests. For instance, annual compensation paid by private insurance companies to forest owners in Finland due to snow damage is on average less than €1 million, while the annual compensation paid due to wind damage has varied during the last 15 years between €1 million and €51 million (Finnish Forest Research Institute, 2014). The direct cost of forest fires in Finland is relatively small because the average annual burned area in the country is only slightly above 500 ha. However, when indirect costs including prevention and suppression of forest fires are also considered, it can be estimated that the total financial cost of forest fires is nearly €7000 per burned hectare (Kosenius et al., 2014; Venäläinen et al., 2016). In a case of a potential widespread forest fire, the costs would thus be substantial. For example, the total cost of the conflagration that burned 14 000 ha of forest in Sweden in 2014 was approximately €100 million, or about €7000/ha (Västmanland County Administrative Board, 2015).

During the forthcoming decades, the climate in northern Europe is projected to change considerably due to increasing greenhouse gas concentrations (e.g. Räisänen and Ylhäisi, 2015). This change may have multiple effects on boreal forests. Climate models unanimously project mean temperature to rise and annual precipitation is also likely to increase. These two forcing factors have an opposite effect on forest fire danger, with increasing temperature likely to increase the risk of fire and increased precipitation likely to reduce the risk of fire. The effect of these anticipated changes on the risk of snow damage is not straightforward. The projected change in the occurrence of strong winds is small but the risk of wind damage is anyway expected to increase because soil frost supporting tree anchorage is projected to decrease drastically (Peltola et al., 2010; Gregow et al., 2011).

In this work, the main objectives were to evaluate the effect of climate change on forest fire risk and the occurrence of snow damage in Finnish conditions by using state-of-the-art climate model data. To complement earlier work in this field, statistically downscaled and bias-corrected data from several newest generation climate models were used. Other recent studies related to the climate change impact on forest fire danger in Finland or nearby areas have mainly considered only multi-model mean change (e.g. Kilpeläinen et al., 2010a; Sherstyukov and Sherstyukov, 2014) or have been based only on scenarios derived from one climate model (e.g. Mäkelä et al., 2014; Yang et al., 2015). In order to study the risk of snow damage in climatological timescales, a crown snow load model developed at the Finnish Meteorological Institute (FMI) was applied.

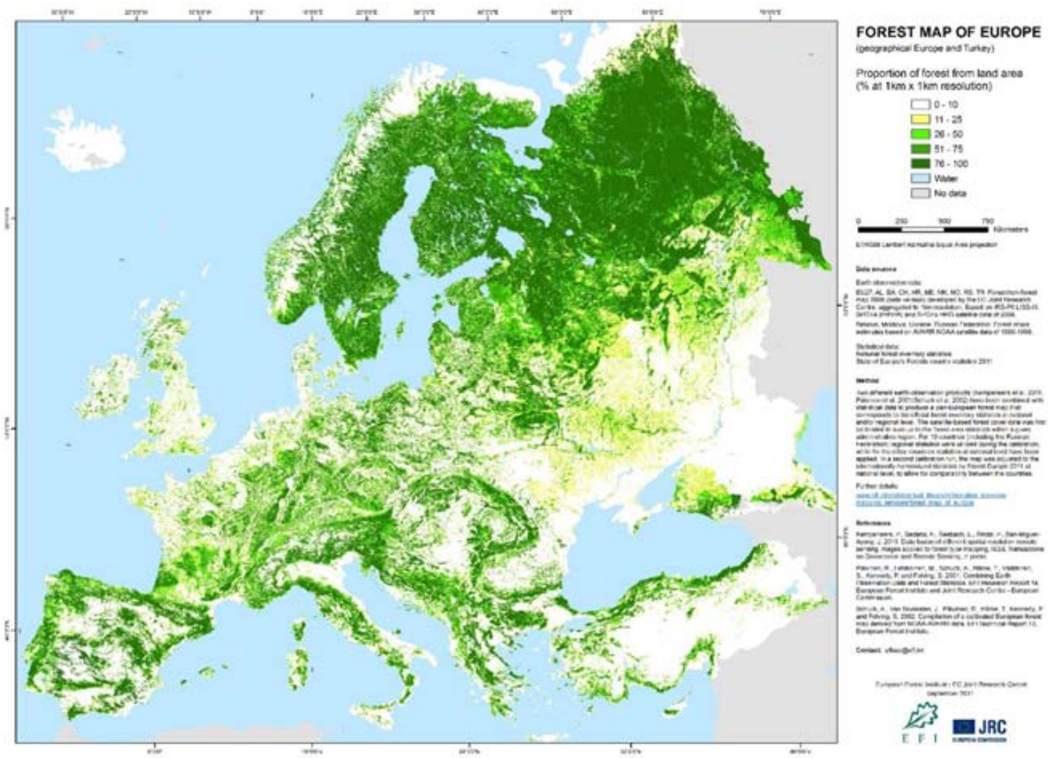

Figure 1. Forest cover map of Europe. Source: Päivinen et al. (2001), Schuck et al. (2002) and Kempeneers et al. (2011).

2. Forest fires in Finland

Finland is part of the vast circumboreal vegetation zone. The extent of the boreal forests is exemplified by the fact that they contain more than 30% of all carbon present in the terrestrial biome (Kasischke, 2000). A natural phenomenon maintaining biodiversity and an important factor in the process of forest regeneration in the circumboreal region is fire (e.g. Rowe and Scotter, 1973; Esseen et al., 1997). It is estimated that globally 5–15 million ha of boreal forests burn annually, primarily in Siberia, Alaska and Canada (Flannigan et al., 2005; Flannigan et al., 2009).

The essential elements needed to cause a forest fire include an igniter, flammable fuels and suitable weather conditions. Lightning is the only natural source of ignition in boreal forests, but in Finland less than 15% of all forest fires are ignited by a lightning strike (Larjavaara et al., 2005). The rest of the fires are human-caused, resulting mostly from careless handling of fire. It is the weather that determines whether the conditions are favourable for the spreading of fires, but it is clear that fire activity is heavily affected by human influence. Consequently, actual fire activity is a complex phenomenon to model.

During previous centuries, fire was intentionally used to clear forest for pasture and cultivation. Accordingly, the number of forest fires increased in Finland in the late 17th century when more people moved into wilderness areas (Wallenius et al., 2004). Slash-and-burn cultivation practices were broadly continued until the late 19th century and the steep decline in forest fire activity at that time across Fennoscandia has been attributed to the cultural transition to modern agriculture and forestry (Wallenius, 2011). Back in the 19th century, large forest fires were common in Finland and, for example, in 1868, over 60 000 ha of state-owned forest was burned within a single year (Saari, 1923; Osara, 1949). The last real conflagration in Finland was the one in Tuntsa in eastern Lapland in 1960 along the Russian border that burned 20 000 ha of forest on the Finnish side of the border and additionally some 100 000 ha on the Russian side (Vajda and Venäläinen, 2005).

Within recent decades, large forest fires have become virtually non-existent in Finland, although there still occurs approximately 1000 forest fires annually (Fig. 2). The average size of forest fires in Finland is nowadays only about 0.5 ha, while it was over 50 ha in many years in the 19th century and early 20th century. Active fire suppression contributes to the small average size of fires. Fire survey flights conducted during periods of high forest fire danger aid the early detection of ignited fires, and due to a dense forest road network firefighters are able to easily reach most of the fires. In addition, the geographical heterogeneity of Finland, with its numerous lakes and swamps creates more natural obstacles for fires compared to many other parts of the boreal zone. However, there has not been any significant change in the climatological fire proneness of Finnish forests during the last century that could explain the decrease in burned area (Mäkelä et al., 2012). From a climatological point of view, large-scale fires are thus still possible in Finland and this was recently demonstrated when 14 000 ha of forest was burned in 2014 in central Sweden in climatological and environmental conditions similar to Finland.

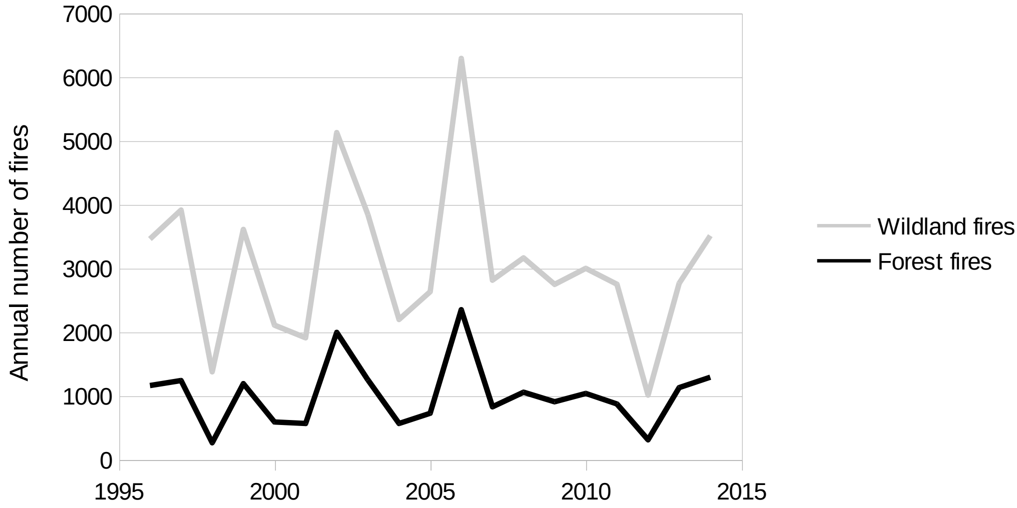

Figure 2. Annual number of forest fires (black) and all wildland fires (grey) including also fires in peat bogs, clear cut sites, parks, grasslands etc. in Finland during 1996–2014 based on fire reports collected from the national Finnish Rescue Service database.

3. Snow damage in forests

Forest damage caused by snow loading on trees occurs frequently in boreal environments. At a European level, estimates of the amount of timber damaged by snow during a typical year vary between 1 million m^3 and 4 million m^3 (Nykänen et al., 1997; Schelhaas et al., 2003). In Finland, snow is one of the most important abiotic stress factors in forests after windstorms. Snow loads sufficient to break individual large tree stems occur in Finland approximately every 3 years to 17 years depending on the location (Solantie, 1994). Snow-damaged trees occasionally seriously disrupt power transmission by bending over or leaning on power lines. For instance, in the beginning of November 2001, over 20 000 damaged trees fell over power lines due to the combined effect of a windstorm and heavy snow loading, and consequently 177 000 households were left without electricity (Hoppula, 2005). Furthermore, snow-damaged trees are susceptible to insect attacks and other kinds of consequential damage (e.g. Schroeder and Eidmann, 1993; Schlyter et al., 2006). Eventually, the reduction of timber quality due to indirect impacts of snow damage may be financially more important than that due to direct impacts.

Suitable meteorological conditions are needed to cause snow damage in forests. The optimal temperature range for the accumulation of snow on tree branches and trunks is relatively narrow, approximately –3°C to +1°C (Solantie, 1994). Snow accretion is most efficient when temperature at the time of precipitation is just above 0°C and then falls below 0°C. In that case, heavy and slightly wet snow attaches tightly to the branches when frozen. According to Solantie (1994), snowfalls of 20–40 cm in temperatures near freezing point produce low to moderate risk of snow damage in forests, while snowfalls of about 60 cm produce very high risk. However, high wind speeds exceeding 9 ms^{-1} are expected to dislodge most of the snow from tree crowns. On the other hand, frozen snow is less effectively dislodged by wind, and thus strong winds associated with heavy frozen snow loads may cause stem breakage (Valinger and Lundqvist, 1992).

Topography has a significant effect on the risk of snow damage. In general, forests at high altitudes accumulate the heaviest snow loads (e.g. Jalkanen and Konôpka, 1998; Jalkanen and Mattila, 2000). This was noted much earlier in the study by Heikinheimo (1920) where he argued that in Finland, forests damaged by snow are mainly located at over 300 m above sea level. This is because the intensity of rime accumulation is strongly correlated with the height above sea level. Ahti (1978) studied rime accumulation in Finland and noted that in northern Finland riming occurs regularly at heights of over 200 m above sea level and that above 500 m the riming is very intense. Jalkanen and Konôpka (1998) studied the influence of altitude on snow packing in Lapland by felling a few average-sized Norway spruces (*Picea abies*) at different altitudes between 150 m and 350 m above sea level in March 1994 and then weighing the actual snow loads that the trees had been carrying. They found that individual trees may carry a snow pack of more than three times the weight of the tree and that the weight of the snow loads on trees increases linearly with the terrain elevation. It has been furthermore argued that tree breakage under extreme snow loading is the major limiting factor at the timberline in northern Finland (Marchand, 1996). At high altitudes, rime accumulation is enhanced because clouds hit the ground more often, which enables in-cloud icing. Secondly, wind speeds are higher on hills than in valleys and the intensity of rime formation is positively correlated with wind speed (Ahti and Makkonen, 1982). Strictly speaking, in-cloud ice loads correlate much better with the elevation in relation to the mean level of surrounding terrain than with the elevation in relation to sea level (Makkonen and Ahti, 1995). Moreover, icing increases with elevation more rapidly on the windward than on the leeward side of hills (Lomilina, 1977). The dependence also varies with region. For instance, in New England ice accretion has been found to increase exponentially with elevation above 800 m (Ryerson, 1990), whereas in central Europe altitudes of 500–900 m are associated with the highest incidence of snow damage and in northern Europe snow damage is already more common above just 100 m (Nykänen et al., 1997). In addition to enhanced rime formation, topography also affects snow loads due to orographic addition to precipitation under suitable conditions. Even in the region of Uusimaa in southern Finland with its relatively flat terrain, the orographic addition to precipitation can be as high as 40–60% during onshore winds (Solantie, 1994).

Typical forms of snow damage in forests include breakage and bending of stems as well as uprooting when the soil is unfrozen (Petty and Worrell, 1981; Nykänen et al., 1997). Tree and stand characteristics, e.g. crown type, stem taper, stem strength and stand density, control the resistance of trees to snow. For example, trees with asymmetrical crowns are particularly susceptible to snow damage (Nykänen et al., 1997). Hence, some tree species are more vulnerable to snow damage than others, and different tree species also suffer from different kinds of damage. In general, conifers are often considered to be more susceptible to snow damage than deciduous trees (Nykänen et al., 1997). Furthermore, Norway spruce is considered to be more resistant to snow damage than Scots pine (*Pinus sylvestris*) because of its more symmetrical crown and lower centre of gravity. Birches (*Betula* spp.)

are vulnerable to bending (Martiník and Mauer, 2012) and can thus easily cause electricity blackouts caused by trees bending over power lines.

The risk of snow damage can be altered by different forest management options. In addition to the choice of species, these include, for example, choice of regeneration method, planting density and thinning policy (Nykänen et al., 1997). In planted stands it is also very important to use local or similarly resistant seed sources. Decreased planting density seems to generally decrease the occurrence of snow damage by stimulating diameter growth. Thinning temporarily increases the susceptibility of a stand to snow damage but promotes taper development. The first thinning should be done when the mean height is 10 m or less. The risk of snow damage can also be minimized by avoiding high-risk silvicultural treatments such as combined thinning and fertilization (Valinger et al., 1993; Nykänen et al., 1997). This is because fertilization promotes increased growth primarily within the tree crowns.

4. Materials and methods

4.1 Data sets

Data sets used in Papers I–IV include climate model data, observational weather data, forest fire statistics (Paper II) and digital images of canopy snow cover from the Hyytiälä forestry field station (Paper III). In Paper III, North Atlantic Oscillation (NAO) index (Visbeck et al., 2001) values were also used.

Climate models are the basic tools for investigating the response of the climate system to various forcings and for making projections of future climate (Flato et al., 2013). Climate models are derived from fundamental physical laws and their outputs can be used to estimate time and space dependent values for a wide set of meteorological and oceanographic variables. The model data collected within the Coupled Model Intercomparison Project (CMIP) can be accessed by the research community worldwide from data archives supported by the Program for Climate Model Diagnosis and Intercomparison (Meehl et al., 2000). In Paper I, the model data from CMIP Phase 3 (Meehl et al., 2007) were used with three forcing scenarios from the Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000). In Papers II and IV, model data from CMIP Phase 5 (Taylor et al., 2012) were used under two representative concentration pathway (RCP) scenarios (van Vuuren et al., 2011).

The direct use of climate model results as such is usually not desirable because model results tend to be biased high or low in relation to the observed climate (e.g. Cattiaux et al., 2013). In addition, they are often presented in a relatively coarse grid. Two common approaches to account for model biases are delta-change and bias correction techniques (e.g. Teutschbein and Seibert, 2012; Räisänen and Räty, 2013). In the delta-change approach, future climate projections are constructed by perturbing the observational time series based on the differences between the simulated baseline and future climates. In this transformation, the daily variations and intervariable relationships of the observational data are retained in a qualitative sense. This approach was applied in Paper I. Bias correction techniques are based on the idea of retaining daily variations of the modelled data by modifying the modelled time series based on the differences between the simulated and observed climate during the baseline period. On the other hand, bias correction alters spatio-temporal relations between different weather variables without satisfactory physical justification (Ehret et al., 2012). In recent studies, the most popular bias correction technique has been quantile mapping (e.g. Teutschbein and Seibert, 2012). In quantile mapping, the simulated values of weather variables are transformed so that the transformed values have the same cumulative distribution as the observed time series. The same transformation is then applied for projected future periods. In Papers II and IV, a gridded data set that was created by applying quantile mapping and downscaled onto a regular 0.1° × 0.2° (~10 km × 10 km) grid covering Finland was used in order to create projections covering the whole country. This data set consisted of daily data from five CMIP5 models over the period 1980–2099 (Table 1). The models were chosen on the basis of their ability to simulate present-day average monthly temperature and precipitation climatology in northern Europe and the availability of all required variables on a daily timescale.

In general, the climate model simulations indicate that in northern Europe, including Finland, temperature and precipitation will increase both in winter and summer, although for precipitation the sign of the change is less certain in summer (e.g. IPCC, 2013; Lehtonen et al., 2014; Räisänen and Ylhäisi, 2015). Projected changes for wind speed and relative humidity are less pronounced but in winter humidity is likely to increase (Gregow et al., 2012; Ruosteenoja and Räisänen, 2013).

Observational climate data sets used include both station and gridded data. Station data were used in Papers I and III. In Papers II and IV, a gridded observational data set was used in statistical downscaling of the model data. The gridded data had been produced by interpolating from the station observations made by the FMI by applying kriging with external drift (Aalto et al., 2013).

Forest fire statistics used in Paper II consisted of fire reports collected from the national Finnish Rescue Service database from 1996 to 2014. The fire reports include information on date, time, location, burned area and ignition source of fires. They also contain information about the vegetation type of the fire sites. Prior to 2005, the locations of fires in the database were in most cases given only at municipality level, but thereafter, the exact coordinates were usually provided. The fire reports were used to build a relationship between fire activity and meteorological fire risk in Finland.

Table 1. CMIP5 models used in Papers II and IV with information on the country of origin and resolution of the models (L refers to number of vertical levels). Adapted from Papers II and IV.

Model	**Country of origin**	**Resolution (long × lat), level**	**Reference**
CanESM2	Canada	1.875° × 1.875°, L35	von Salzen et al. (2013)
CNRM-CM5	France	1.4° × 1.4°, L31	Voldoire et al. (2013)
GFDL-CM3	United States	2.5° × 2.0°, L48	Donner et al. (2011)
HadGEM2-ES	United Kingdom	1.25° × 1.875°, L38	Collins et al. (2011)
MIROC5	Japan	1.4° × 1.4°, L40	Watanabe et al. (2010)

In Paper III daily digital images of canopy snow cover from the Hyytiälä forestry field station located in the region of Pirkanmaa were utilized. The images encompassed three consecutive winter seasons (2008/09–2010/11) and were visually classified into six classes by forest scientists based on the amount of snow and rime or hoar frost in the canopy (Kuusinen et al., 2012). This classification was then used in comparison with the snow load calculations.

4.2 Forest fire risk assessment

There exist various indices which can be used in the prediction of forest fire risk. In boreal conditions, probably the most widely used is the so-called Canadian Fire Weather Index (FWI) system (Van Wagner, 1987). In the FWI system, three moisture codes are calculated on a daily basis based on air temperature, relative humidity, wind speed and precipitation (Table 2). Then, affected by wind speed, these codes are converted into three fire behaviour indices (Fig. 3). Initial Spread Index (ISI) indicates the expected rate of fire spread and Build Up Index (BUI) the total amount of fuel available for combustion by a moving flame front (De Groot, 1987). The final FWI rating is a dimensionless quantity combining ISI and BUI and indicates the likely intensity of fire. The FWI system was applied in Papers I and II to assess the meteorological forest fire risk following Van Wagner and Pickett (1985). Additionally, in Paper I the results of experimental ignition studies of Tanskanen et al. (2005) were used to estimate the annual number of potential fire days in different forest stands with the help of the FWI system.

Table 2. Fuel moisture codes in the FWI system (adapted from De Groot 1987).

Item	**Fine fuel moisture code (FFMC)**	**Duff moisture code (DMC)**	**Drought code (DC)**
Fuel association	Litter and other cured fine fuels	Loosely-compacted organic layers of moderate depth	Deep, compact organic layers
Fire potential indicator	Ease of ignition	Probability of lightning fires; fuel consumption in moderate duff	Mop-up difficulty; fuel consumption of deep organic material
Depth	1–2 cm	5–10 cm	10–20 cm
Timelag constant	16 hours	12 days	52 days
Value range	0 (wet) to 99 (dry)	0 (wet) to infinity (dry)	0 (wet) to infinity (dry)
Maximum probable value	96	150	800

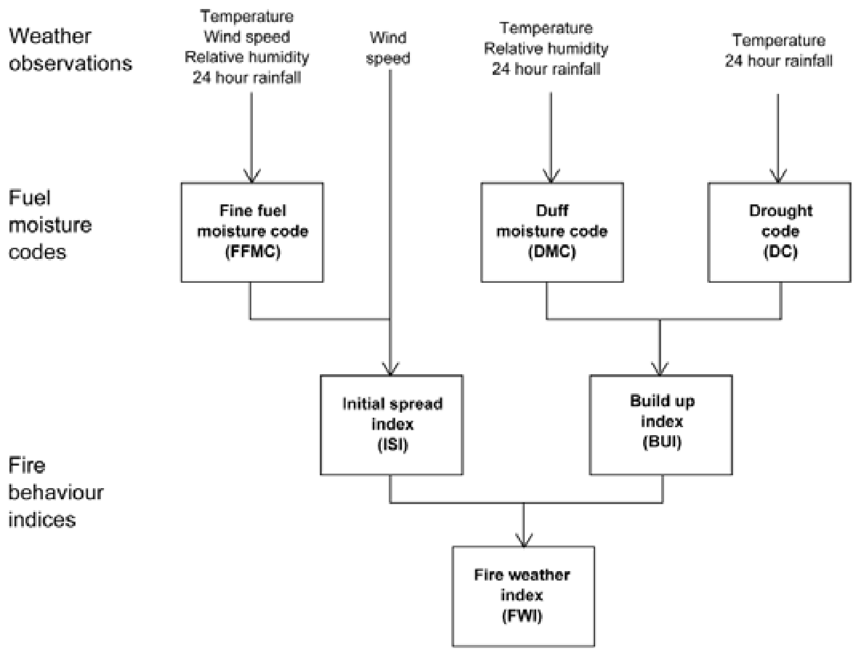

Figure 3. Schematic calculation structure of the Canadian Fire Weather Index (FWI). Adapted from Paper I.

The FWI system was initially developed empirically for Canadian boreal conditions. However, the FWI indices have proved to be realistically linked to the moisture content of different forest fuels in many kinds of environments (Viegas et al., 2001) and the FWI system has become widely implemented in many countries around the world, including New Zealand (Pearce and Clifford, 2008), Spain (Padilla and Vega-Garcia, 2011) and Greece (Dimitrakopoulos et al., 2011), for example. The FWI system has also been suggested as the basis for a global early warning system for wildland fires (De Groot et al., 2006). In Finland, forest fire warnings are issued based on the Finnish Forest Fire Index (FFI) model (Venäläinen and Heikinheimo, 2003), but comparison of FWI to FFI has revealed that in Finnish conditions the two indices have a similar performance (Vajda et al., 2014).

4.3 Snow load risk assessment

In assessing the risk of snow damage, a model developed at FMI to predict snow load amounts on tree crowns was used in Papers III and IV. The development of the FMI snow load model is based both on experimental work and empirical experience of several experts at FMI. The model has run operationally since 2006 and the parameters of the model have been tuned based on the experience of model performance in different weather situations. The model parameters are thus mainly empirical. The model assumes an idealized tree having a cone-shaped crown with a projected catchment area of 1 m^2 from above and from the side facing the wind.

Table 3. Threshold values of daily mean 2 m air temperature (T_{mean}), 2 m relative humidity (RH_{mean}), 10 m wind speed (U_{mean}) and total precipitation (P_{day}) that were used to determine the risk days favourable for heavy snow loading and riming. Adapted from Paper III.

Snow loading	**Riming**
$-3.42°C < T_{mean} < 1.05°C$	$-5.19°C < T_{mean} < -0.16°C$
$RH_{mean} > 89.44\%$	$RH_{mean} > 95.50\%$
$2.07\ ms^{-1} < U_{mean} < 5.63\ ms^{-1}$	$2.00\ ms^{-1} < U_{mean} < 4.54\ ms^{-1}$
$P_{day} > 6.41$ mm	$P_{day} < 1.11$ mm

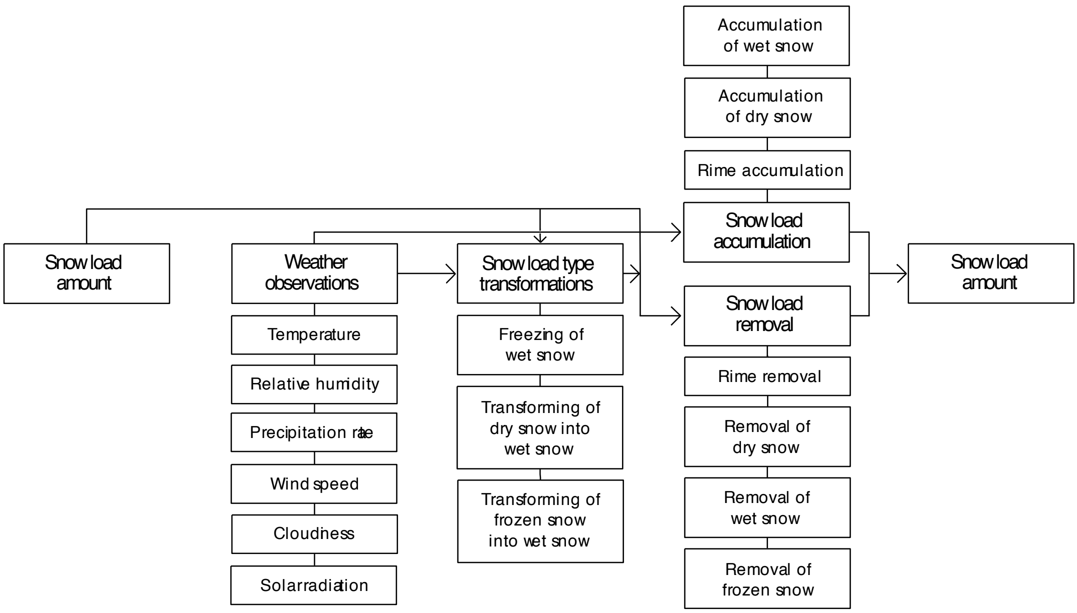

Figure 4. Schematic structure of the FMI snow load model.

The schematic structure of the FMI snow load model is presented in Fig. 4. The model has a time step of one hour and it uses temperature, relative humidity, precipitation rate, wind speed, cloudiness and solar radiation as input variables. Rime accretion in the model is also affected by terrain elevation. The snow load is classified into four types: rime, dry snow, wet snow and frozen snow. First, part of the existing snow load is transformed into a different type if needed and then the snow load is increased and decreased because of snow accretion and removal. Depending on air temperature, accumulated snowfall is treated as wet or dry snow and wet snow can be later frozen if temperature drops below 0°C. Decrease of the snow load is caused by dropping and melting due to wind and thaw. A detailed description of the applied model version is presented in the appendix of Paper III.

The snow load amounts calculated with the FMI snow load model were also compared with a simpler snow load model presented by Gregow et al. (2008). Compared to the FMI model, there are two main deficiencies in that model. Firstly, rime accumulation is not taken into account and secondly, the snow load is not classified into different types.

In addition to the modelled snow load amounts, the snow-damage risk was evaluated based on daily average values of temperature, relative humidity, wind speed and precipitation. The thresholds (Table 3) for each variable were defined based on weather observations and modelled snow loads at four locations. These thresholds were used as a proxy for heavy snow loading and rime accumulation.

5. Results

5.1 Forest fire risk

Climate change impact on forest fire risk in Finland during the 21st century was studied in Papers I and II. In Paper I, the focus was to study the differences in the risk between different greenhouse gas scenarios and between different forest stands. In Paper II, the main target was to inspect the inter-model variability of the projected change of fire danger and also to pay special attention to large-scale fires.

Three SRES scenarios (Nakićenović et al., 2000) were considered in Paper I, B1 representing low, A1B medium and A2 high greenhouse gas emissions. The forest fire risk was studied at four locations (Vantaa, Jokioinen, Jyväskylä and Sodankylä) across Finland (Fig. 1 in Paper I) during the baseline period 1980–2009 and during three future periods (2015–2044, 2035–2064 and 2085–2114). The annual number of days with high or extreme forest fire risk according to the FWI system varied greatly

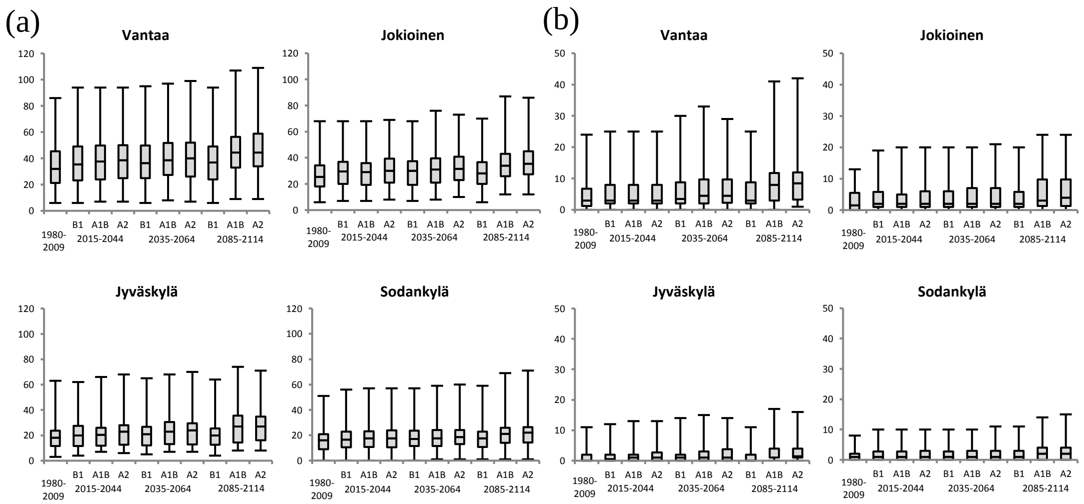

Figure 5. Annual number of days with (a) a high or extreme, and (b) an extreme FWI value in the baseline period 1980–2009 and in the scenario periods as a response to the various greenhouse gas scenarios. The boxes indicate the central 50% range and the median of the distribution. The whiskers extend to the minimum and maximum values. Adapted from Paper I.

between different years within the baseline period (Fig. 4 in Paper I). Typically, there were about 20–40 such days annually at southern locations (Vantaa and Jokioinen) and less than 20 at Jyväskylä in central and Sodankylä in northern Finland (Fig. 5). However, during the wettest years, the annual count of these forest fire risk days was less than 10 at each location and during the driest years it varied from approximately 50 at Sodankylä to over 80 at Vantaa.

In the forthcoming decades, the annual number of forest fire risk days was projected to increase to some extent (Fig. 5). By the end of the current century, the increase in the annual number of days with high or extreme forest fire danger varied between 10% and 40%, depending on the greenhouse gas scenario. The smallest changes were projected under the low-emission B1 scenario, while the projected changes under the A1B and A2 scenarios were rather similar. When considering only days with extreme forest fire danger, the annual median number of such days was projected to more than double by 2100. However, when compared with the large interannual variability in the forest fire danger in Finland, the projected changes were not particularly substantial.

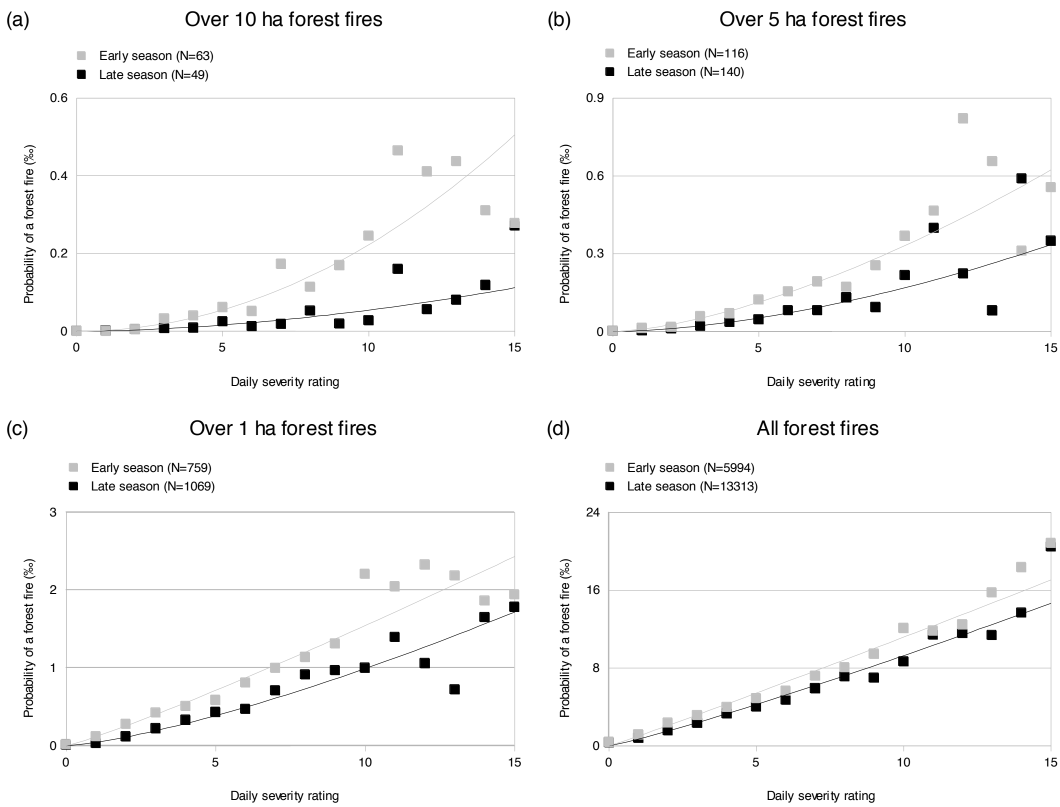

Figure 6. The relationship between daily severity rating and occurrence of forest fires of different size in Finland during 1996–2014, performed separately for the early (effective temperature sum below 250°C days; grey squares) and late season (effective temperature sum above 250°C days; black squares). (a) Forest fires over 10 ha. (b) Forest fires over 5 ha. (c) Forest fires over 1 ha. (d) All forest fires. The number of fires in each class is shown in parentheses. Adapted from Paper II.

The number of fire risk days varied greatly between different types of forest stands (Fig. 6 in Paper I). In general, Scots pine stands showed much higher fire potential than Norway spruce stands. In addition, the number of potential fire days was two to three times greater at clear-cut sites compared to stands with a closed canopy. Future projections indicated a slight increase in the fire risk at different forest stands. However, even for the furthermost future period around the year 2100 under high-emission A2 forcing, only 5–10 additional fire danger days were projected at most.

To conclude the results of Paper I, it can be stated that assuming the high-emission A2 scenario to be realized, the current forest fire risk levels at Vantaa, Jokioinen and Jyväskylä would be transposed during the next 100 years northwards to Jokioinen, Jyväskylä and Sodankylä, respectively.

In Paper II, it was found that fire activity correlates reasonably well with meteorological fire danger in Finland (Fig. 6). Average size of forest fires moreover increases with increasing fire danger (Table 4 in Paper II). Consistently with previous studies (Tanskanen and Venäläinen, 2008), it was also noted that there occur more forest fires with the same FWI index value in the beginning of the growing season before understorey vegetation is fully developed than later in summer. This difference appeared to be clearer the larger the fires that were inspected.

The fire statistics moreover revealed interesting seasonality in the cause of forest fires. The peak in the occurrence of relatively large fires burning over 10 ha of forest in Finland is in the latter half of May and early June. These fires are almost entirely human-caused, mainly because of silvicultural slash burning of cured vegetation and rubbish. During this time of year, the correlation between fire danger and burned area was found to be weakest. Burned area can be best estimated on the basis of the FWI system in July when lightning is a more important cause of ignitions than in any other month. Forest fires in July are still mostly human-caused (Fig. 7), but the majority of fires larger than 10 ha in July were reportedly ignited by a lightning strike during 1996–2014 (Fig. 7c in Paper II). The annual occurrence of lightning-ignited forest fires was generally found to closely follow the annual cycle of lightning activity.

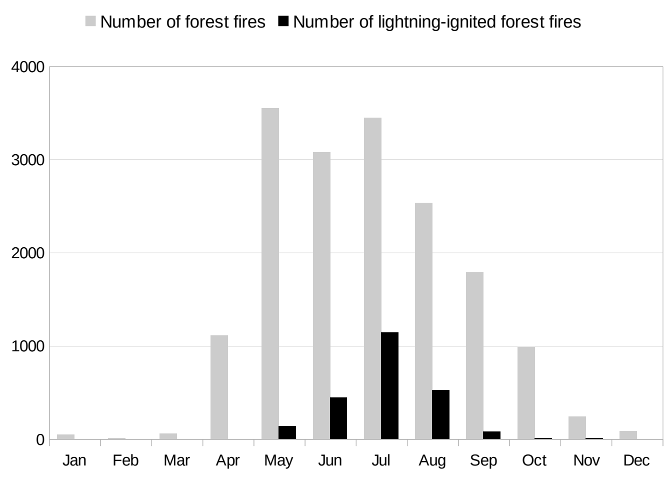

Figure 7. Monthly total number of all forest fires (grey) and forest fires that were reportedly ignited by a lightning strike (black) in Finland during 1996–2014 based on fire reports collected from the national Finnish Rescue Service database.

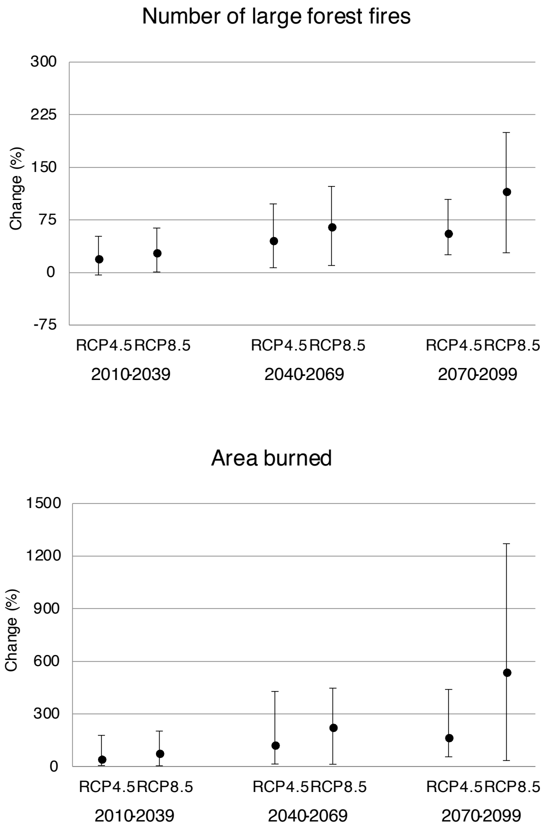

Figure 8. Projected change in the annual number of large (over 10 ha) forest fires and area burned in Finland compared to the period 1980–2009. Dots indicate the multi-model mean change and whiskers extend to the maximum and minimum projections among the five models. Adapted from Paper II.

The relationship between observed fire activity and fire danger during 1996–2014 was used to estimate the expected change in future fire activity as a response to projected climate change. The results indicated increasing fire danger towards the end of the present century (Fig. 8). On the other hand, there existed substantial inter-model variability in the projected change. Moreover, as a few large-scale fires can be responsible for a large majority of burned area, a rather small increase in the number of large fires may lead to a substantial increase in the burned area. The results of Paper II reflected that the uncertainties related to changes in temperature, precipitation, wind and humidity climates all add uncertainty to the estimation of forest fire danger. This was illustrated by the large differences in the future forest fire danger between the outputs of the selected climate models. However, none of the models indicated a decreasing trend in forest fire danger. Based on the results, the proportion of large-scale fires will most likely increase. This would further increase the pressure on fire management agencies to be able to suppress the fire efficiently.

5.2 Heavy snow loads

The risk of snow damage in forests was studied mainly based on the FMI snow load model. This model was presented in Paper III. The model performance was evaluated against the canopy snow classification from the Hyytiälä forestry field station and the performance was further demonstrated with the help of two case studies. Based on comparison with the canopy snow classification, it was not obvious that the FMI snow load model would perform better than the simpler method (hereafter G08 method) presented by Gregow et al. (2008). The simulated snow loads by both methods increased, on average, with increasing canopy snow amounts. However, the modelled snow loads varied considerably within individual snow classes, especially when the tree canopies were partially snow-covered. When the canopies were fully covered by snow, the modelled snow loads also consistently tended to be rather heavy. Similarly, the modelled snow loads were relatively low when most of the canopies were snow-free. In the case that canopies were otherwise snow-free but covered by rime, the FMI snow load model clearly indicated heavier snow loads than the G08 method, which did not take riming into account. This was best demonstrated during early December 2009 when very favourable conditions for rime accumulation prevailed for several days.

Spatial occurrence of heavy snow loads was studied in Paper III based on station observations from 29 locations across Finland over the period 1961–2010. The snow loads calculated at each station were interpolated over the whole country by applying kriging interpolation with external drift (Aalto et al., 2013). In Paper IV, the snow loads were calculated directly from gridded weather data. The weather data covered observational data for the period 1981–2010 and downscaled model data for the years 1980–2099. The gridded weather data used in Paper IV had a temporal resolution of 24 hours, while the station observations used in Paper III were mainly available every 3 hours and daily values were used only for precipitation.

The large-scale features of Finnish snow load climatology were similar based on the results of Papers III and IV. In general, the heaviest snow loads tend to occur in eastern parts of the country in the regions of North Karelia, Kainuu and Koillismaa as well as in eastern Lapland. The results of Paper IV also emphasized the area of north-western Lapland where rime loads were modelled to be particularly heavy. The weather stations used in Paper III probably did not well enough represent this area, which has much more complex topography than other parts of Finland.

It appeared that the snow load amounts calculated by using the G08 method correlate best with the dry snow loads of the FMI snow load model (Table 4). Regarding the snow damage in forests, dry snow is, however, the least important snow load type because dry snow is light and easily blown away by wind. Thus, the heaviest dry snow loads are considerably lighter than wet and frozen snow loads or rime loads (Fig. 7 in Paper III and Fig. 4 in Paper IV). As the G08 method does not take riming into account, the snow loads the method produces are only weakly correlated with the rime loads calculated with the FMI snow load model (Table 4).

Table 4. Correlation coefficients between daily values of different snow load types of the FMI snow load model and total snow loads calculated by using the G08 method at four locations in Finland over the period 1980–2009.

	Vantaa	**Jokioinen**	**Jyväskylä**	**Sodankylä**
Rime load	0.21	0.29	0.34	0.29
Dry snow load	0.73	0.74	0.74	0.78
Wet snow load	0.52	0.47	0.41	0.23
Frozen snow load	0.55	0.61	0.56	0.45

It was found in Paper III that seasonal mean relative humidity has a positive correlation with all kinds of snow load types, while wind speed is negatively correlated with snow loads. The strongest positive correlation was found between relative humidity and rime loads and the strongest negative correlation between wind speed and dry snow loads (Paper III, Table 4). Also, precipitation and wet snow loads were clearly positively correlated. Temperature seemed to have in general only a rather weak influence on the snow load amounts. In southern Finland, heavy snow loads were more often associated with cold winters and a negative phase of the NAO, while in northern Finland mild winters with positive NAO index values posed a somewhat greater risk of heavy snow loads. There were furthermore some differences in the correlations with seasonal temperatures between different snow load types. Wet snow loads, and in northern Finland also frozen snow loads, tend to be heaviest during relatively mild winters, while the heaviest dry snow loads, and in the south also rime loads, were found to occur during cold winters.

The number of risk days for heavy snow loading on the basis of daily mean values of different weather variables proved to predict well the number of days with modelled heavy snow load accretion (Fig. 9 in Paper III). For the risk days for heavy rime accretion this held true for most of the inland stations. On the other hand, the maritime stations and particularly the stations in northern Finland located at high elevations exhibited clearly too few risk days for heavy rime accretion based on the threshold values used.

The future snow load projections indicated that heavy snow loads will clearly decrease in southern and western Finland as a response to projected climate change (Fig. 9). On the contrary, in north-eastern parts of the country, the snow loads were projected to become heavier indicating increasing risk of snow-induced forest damage over the area. There was some variability in the rate of projected change among the five climate models used in the study, but the large-scale picture of the change was similar according to all the model simulations.

It is moreover noteworthy that the geographical pattern of projected change was fairly similar for heavy rime loads and heavy wet and frozen snow loads. Considering the multi-model mean change until the end of the present century under the high-emission RCP8.5 scenario, all of these snow load components were projected to increase in eastern and northern Finland including roughly the regions of North Karelia, Kainuu, Koillismaa and Lapland (Fig. 9). Elsewhere in Finland, they were projected to decrease. The heaviest dry snow loads were projected to change somewhat differently as they were projected to decrease across almost the whole of Finland. Only in Lapland were they projected to remain virtually unaltered. Moreover, the projected changes for dry snow loads resembled closely those for total snow loads calculated using the G08 method.

The weather conditions favourable for rime accretion occur most commonly in early winter (Fig. 10 in Paper III). In southern Finland, this period extends roughly from November to January but in the north the seasonal peak is earlier, in October and November. In a warmer climate, this peak is expected to be shifted slightly later in winter so that December and January would become the months expressing the highest risk of heavy rime accretion in central and northern parts of Finland (Fig. 7 in Paper IV).

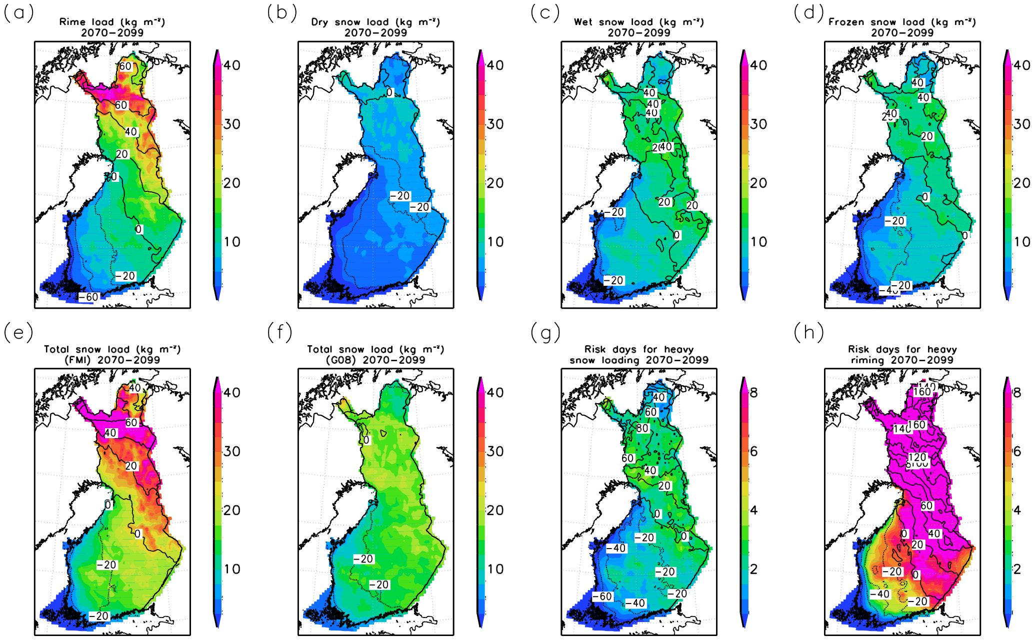

Figure 9. The average annual maximum rime loads (a), dry snow loads (b), wet snow loads (c), frozen snow loads (d), total snow loads based on the FMI snow load model (e) and total snow loads based on the G08 method (f) for the period 2070–2099 under the RCP8.5 scenario as a multi-model mean. The average annual number of risk days for heavy snow loading (g) and heavy riming (h) are shown as well. Contours show the multi-model mean percentage change from 1980–2009 to 2070–2099. Adapted from Paper IV.

Wet snow hazards occur more often both in early and late winter when the mean temperature is closer to the freezing point than in midwinter. In the future, their occurrence is expected to increase during the coldest part of winter but decrease in early and late winter.

6. Discussion and conclusions

This thesis contributes to the understanding of climate change impact on the occurrence of forest fires and heavy snow loads in Finland. These results can be utilized when considering climatically-driven abiotic risks in forest management.

It was found that variations in forest fire activity in Finland have been closely related to weather variations within the last about 20 years. If a similar relationship between weather and fire activity holds for the next 100 years, it could lead to a considerable increase in the number of forest fires in Finland assuming the current climate projections are realized. However, the results also emphasized the large uncertainty related to the forest fire projections originating from the variations between different climate model simulations. Moreover, as climate is only one factor affecting fire activity, other factors may be more important in the long term. This is illustrated by the dramatic decline in annual burned area in Finland after the 19th century (Wallenius, 2011) without any significant change in the climatological fire proneness of Finnish forests at the same time (Mäkelä et al., 2012).

The results of climate change impact on forest fire risk are in accordance with previous studies in the field. Kilpeläinen et al. (2010a) estimated that the annual number of forest fires in Finland could increase by approximately 20% during the present century due to climate change. Mäkelä et al. (2014) similarly concluded that the number of fire danger days will most likely increase. As not only the fire frequency, but also the average size of forest fires tends to increase with increasing fire danger, the change in burned area is expected to be larger than the change in the number of fires.

The projected increase in forest fire risk is evidently due to the projected increase in temperature leading to enhanced evaporation from and reduced moisture content of forest fuels. The fire season is moreover expected to start earlier in the future because of earlier snow melt. In addition to temperature increase, also slightly decreasing summertime relative humidity contributes to the projected increase in fire risk. For future wind speed changes, climate models do not have a uniform signal. Precipitation is mostly projected to increase in Finland throughout the year. However, in the south, the change is small in summer and might even be negative.

Weather conditions favouring heavy snow loading and rime accretion on tree crowns were projected to become more frequent in northern Finland and in the regions of North Karelia and Kainuu near the Russian border. In contrast, in southern and western Finland, particularly in coastal areas, snow loads were projected to decrease. The areas experiencing increasing risk of heavy snow loads are mostly those where heaviest crown snow loads already occur in the present climate. An important reason for the heavy snow loads over these areas is that they are susceptible to rime accumulation because of relatively high terrain elevation. The projected changes in snow load amounts appeared to be linked to the climatological mean temperature as snow loads were projected to increase over the areas experiencing the coldest winters in Finland. Over these areas both heavy wet snow loads and rime loads were projected to increase. The results suggest that in the risk areas the possibility of snow damage should be taken into account in forest management when considering, for example, regeneration and thinning options.

Projections for heavy snow loading contradicted the previous conclusion of Kilpeläinen et al. (2010b) that the risk of snow damage in forests would decrease virtually over the whole of Finland. This was because Kilpeläinen et al. (2010b) used the G08 method, which was shown to correspond mainly to the dry snow load component of the FMI snow load model. Gregow et al. (2008) had previously concluded that the risk of heavy snow loads would increase during the late 20th century. However, any significant trend in the heavy snow loads during the last 50 years could not be detected in Paper III when considering only the stations where observed wind speeds did not show a significant and presumably artificial trend. On the other hand, the snow load projections were in accordance with previous model studies considering heavy snowfalls. It has been shown that based on the climate models, maximum snowfall tends to increase with increasing temperature approximately over the areas where monthly mean temperature is below −8°C (de Vries et al., 2014; Räisänen, 2016).

There was in general less variability among model results in snow load projections compared to the forest fire risk projections. However, many sources of uncertainty still exist also in snow load projections. As snow accumulation on tree crowns is most effective in a narrow temperature range close to 0°C, the snow load calculations are sensitive to the weather conditions near freezing point. Furthermore, the snow load models are not perfect and they approximate the amount of snow on idealized tree crowns. The analyses were moreover restricted by the spatial and temporal resolution of climate model data. Better verification of the snow load model would be also beneficial, for example on the basis of detailed national forest inventory data.

The results of this thesis provide support for estimating future occurrence probabilities of fire and snow hazards in Finnish forests. These risks can be reduced by proper forest management, although climate change is in any case predicted to foster forest growth in Finland (Kellomäki et al., 2008). For example, an uneven-aged management system makes forests more vulnerable to the spread of crown fires (Lindberg et al., 2011). In addition to the increasing fire risk, increased droughts may threaten the health of forests (e.g. Gao et al., 2016). In particular, Norway spruce is expected to suffer on less fertile sites (Kellomäki et al., 2008). Boreal forests are, moreover, susceptible to other abiotic and biotic risks than those considered in this thesis. Decreasing wintertime ground frost will make the forests more vulnerable to windstorms (Gregow et al., 2011) and, on the other hand, lack of ground frost may reduce the carrying capacity of soil for timber harvesting (Kellomäki et al., 2010). In summer, pest insects may benefit from increasing temperatures (e.g. Logan et al., 2003; Jönsson et al., 2009).

Summaries of the original publications

The contents of Papers I–IV and the author's contribution are summarized here.

I Lehtonen, I., K. Ruosteenoja, A. Venäläinen and H. Gregow (2014). The projected 21st century forest fire risk in Finland under different greenhouse gas scenarios. *Boreal Environment Research*, **19**: 127–139.

Paper I examines the future forest fire risk at four locations in Finland under three alternative greenhouse gas scenarios and in different forest stands typical of the northern boreal zone. The author was responsible for the calculations and analyses of the results. The author was also mainly responsible for the writing.

II Lehtonen, I., A. Venäläinen, M. Kämäräinen, H. Peltola and H. Gregow (2016). Risk of large-scale fires in boreal forests of Finland under changing climate. *Natural Hazards and Earth System Sciences*, **16**: 239–253.

Paper II estimates the impact of projected climate change on the burned area and risk of relatively large-scale fires in the Finnish forests. The paper moreover studies the climate model based uncertainty in the forest fire risk projections. The climate change impact is estimated by studying the relationship between observed fire activity and weather conditions in the present climate and assuming a similar relationship to hold in the future. The future climate projections are based on statistically downscaled global climate model data. The author was responsible for the calculations, data analysis and writing, excluding most of the work concerning bias correction and downscaling of the climate model data.

III Lehtonen, I., P. Hoppula, P. Pirinen and H. Gregow (2014). Modelling crown snow loads in Finland: a comparison of two methods. *Silva Fennica*, **48**: 1120.

Paper III describes the FMI snow load model and presents the crown snow load climatology of Finland. The author was responsible for all the snow load calculations and writing.

IV Lehtonen, I., M. Kämäräinen, H. Gregow, A. Venäläinen and H. Peltola (2016). Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change. *Natural Hazards and Earth System Sciences*, **16**: 2259–2271.

Paper IV presents the projections for future crown snow loads in Finland using the same statistically downscaled set of climate model data that was applied in Paper II. The author was responsible for the snow load calculations, data analysis and writing.

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