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Risk of large-scale fires in boreal forests of Finland under changing climate

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Abstract. The target of this work was to assess the impact of projected climate change on forest-fire activity in Finland with special emphasis on large-scale fires. In addition, we were particularly interested to examine the inter-model variability of the projected change of fire danger. For this purpose, we utilized fire statistics covering the period 1996–2014 and consisting of almost 20 000 forest fires, as well as daily meteorological data from five global climate models under representative concentration pathway RCP4.5 and RCP8.5 scenarios. The model data were statistically downscaled onto a high-resolution grid using the quantile-mapping method before performing the analysis. In examining the relationship between weather and fire danger, we applied the Canadian fire weather index (FWI) system. Our results suggest that the number of large forest fires may double or even triple during the present century. This would increase the risk that some of the fires could develop into real conflagrations which have become almost extinct in Finland due to active and efficient fire suppression. However, the results reveal substantial inter-model variability in the rate of the projected increase of forest-fire danger, emphasizing the large uncertainty related to the climate change signal in fire activity. We moreover showed that the majority of large fires in Finland occur within a relatively short period in May and June due to human activities and that FWI correlates poorer with the fire activity during this time of year than later in summer when lightning is a more important cause of fires.

1 Introduction

Fire is one of the major natural disturbances affecting forest dynamics and biodiversity in boreal conditions (e.g. Granström, 2001; Kuuluvainen, 2002). Globally, over 10 million hectares of boreal forest burns during a typical year; mostly in Siberia, Canada, and Alaska (Flannigan et al., 2009). A small number of large-scale fires are responsible for a large part of the burned area. For example, in Canada, fires larger than 200 ha represent 3 % of the total number of fires but account for 97 % of the total area burned (Stocks et al., 2002). Since small fires are much easier to control than large fires, it is essential for fire management agencies to try to suppress forest fires before they escalate to large fires that pose a risk for devastating-scale conflagrations.

In Finland, suppression of forest fires has been effective during the recent decades. Although roughly about 1000 forest fires occur annually in Finland, the average size of fires is less than 1 hectare. Fire survey flights contribute to the early detection of ignited fires and the dense forest road network in Finland aids fire fighters to reach and suppress the fires. During the nineteenth century and early twentieth century, large forest fires were still not uncommon in Finland. Back then, the average size of forest fires was over 50 ha in many years and, for instance, in 1868, over 60 000 ha of state-owned forest was burned within a single year (Saari, 1923; Osara, 1949). The steep decline in forest fires across Fennoscandia in the late nineteenth century has been attributed to the cultural transition to modern agriculture and forestry (Wallenius, 2011). At the same time, no significant change in the climatological fire proneness of Finnish forests has been observed (Mäkelä et al., 2012), illustrating that the possibility of conflagrations under the current climatological conditions still exists. This was recently demonstrated in 2014, when a single fire in Västmanland in central Sweden burned 15 000 ha of forest in climatological and environmental conditions similar to Finland.

In determining the risk of forest fires, weather and climate play a key role, along with the fuel amount. High temperatures accompanied by low relative humidity and strong winds enhance the evaporation and drying of the soil and continue to make forest fuels easily flammable. Natural sources, i.e. lightning strikes, ignite less than 15 % of all forest fires in Finland (Larjavaara et al., 2005), and although human activities are responsible for most forest fires, weather makes the conditions favourable for the occurrence and spreading of fires. Studies of historical fire records (e.g. Power et al., 2008; Olsson et al., 2010) have moreover linked changes in fire activity to climatic variations before any human impact was present, illustrating the crucial role of climate on fire activity. Furthermore, increased large fire activity in Canada and Alaska during the late twentieth century has been attributed to increased drought in the area (Xiao and Zhuang, 2007).

In response to global warming, the forest-fire danger is generally projected to increase in the circumboreal region, which may hamper the effectiveness of fire management (e.g. Flannigan et al., 2009). Recent studies have indicated that the forest-fire danger will also most likely increase in Finland due to global warming (Kilpeläinen et al., 2010; Lehtonen et al., 2014b; H. M. Mäkelä et al., 2014), as well as in neighbouring Russia (Sherstyukov and Sherstyukov, 2014); whereas Yang et al. (2015) concluded that northern Sweden will have a lower risk of forest fire in the future. These studies were based either on multi-model mean response (Kilpeläinen et al., 2010; Lehtonen et al., 2014b; Sherstyukov and Sherstyukov, 2014) or basically only on one climate model (H. M. Mäkelä et al., 2014; Yang et al., 2015). Moreover, only Yang et al. (2015) used simulated climate data on a daily timescale, making it possible to take predicted changes in climate variability into account when assessing the changes in forest-fire danger.

To complement the above-mentioned studies, we estimate the impact of climate change on forest-fire danger in Finland by using daily input from five independent general circulation models (GCMs). This allows us to explore the uncertainty ranges related to the projected change in forest-fire danger, an aspect that is poorly covered in the previous studies. In spite of the continuous development of climate models, the range of model uncertainty has not considerably decreased since the 1990s (Räisänen and Ylhäisi, 2015) and with lead times of a few decades, this model uncertainty can account for more than half of the total uncertainty related to climate projections (Hawkins and Sutton, 2009). As the previous studies have, in addition, mainly focused on changes in mean conditions, we direct our special interest to large-scale fires which are more relevant with regard to fire management and ecological consequences. We are moreover motivated by the fact that in countries like Finland, forest-based bioeconomy has a key role in climate change mitigation and it is thus particularly important to understand the impact of climate change on the risks affecting forests and to take them into account in forest management. That is because efficient mitigation requires increasing carbon sequestration and use of forest biomass to substitute fossil-intensive fuels, materials, and products (Kilpeläinen et al., 2015).

In this work, we first use forest-fire statistics from Finland covering 19 fire seasons to study the relationship between weather and fire occurrence in the present climate. Then, we use daily data from five GCMs participating in the Coupled Model Intercomparison Project (CMIP) phase 5 (Taylor et al., 2012) under representative concentration pathway (RCP) scenarios RCP4.5 and RCP8.5 (van Vuuren et al., 2011) to study the impact of climate change on fire occurrence over the period 1980–2099. An intrinsically similar approach has previously been used in studying the impact of climate change on regional fire activity, e.g. by Pereira et al. (2013). In this work, modelled values of weather variables are downscaled onto a high-resolution grid covering Finland using the quantile-mapping approach. In assessing the forest-fire potential, we apply the widely used Canadian forest-fire weather index (FWI) system (Van Wagner, 1987), which provides a numerical rating of fire danger, as well as indices for the moisture content of forest fuels.

2 Materials and methods

2.1 Fire statistics

To study the spatial and temporal occurrence of forest fires in Finland, we used fire data that consisted of fire reports collected from the national Finnish Rescue Service database, available from 1996 onwards. The fire reports include information on date, time, location, burned area, and ignition source of a fire, as well as vegetation type (e.g. forest, clearing, peat land, grassland, park) of a fire site. In this study, we only consider those fires that reportedly burned forested area. The fires that occurred in the autonomous Åland Islands (the group of islands located in the south-westernmost part of Finland, consisting of about 0.5 % of the Finnish land area) were not included in the database.

In most cases, the locations of fires were only given at municipality level prior to 2005, but thereafter, the exact coordinates of the fire sites were usually provided. In this study, the fires were located on a $0.1^\circ \times 0.2^\circ$ (approximately $10\,\mathrm{km} \times 10\,\mathrm{km}$) latitude–longitude grid. In cases when the spatial coordinates were missing, the fires were assumed to be located in the centroid of the municipality where they had occurred.

According to the statistics, almost 20 000 forest fires occurred in Finland from 1996 to 2014. Indeed, 112 of these

Table 1. CMIP5 models used in this study with information on country of origin and resolution of the models (L refers to number of vertical levels, T to triangular truncation, and C to cubed sphere).

Model	Country of origin	Resolution (long × lat), level	Reference
CanESM2	Canada	T63 (1.875° × 1.875°), L35	von Salzen et al. (2013)
CNRM-CM5	France	T127 (1.4° × 1.4°), L31	Voldoire et al. (2013)
GFDL-CM3	United States	C48 (2.5° × 2.0°), L48	Donner et al. (2011)
HadGEM2-ES	United Kingdom	1.25° × 1.875°, L38	Collins et al. (2011)
MIROC5	Japan	T85 (1.4° × 1.4°), L40	Watanabe et al. (2010)

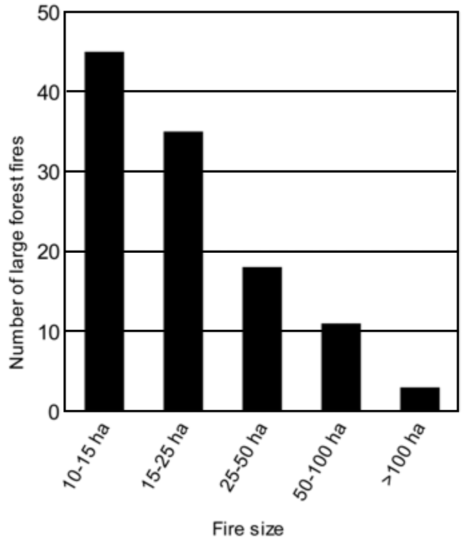

Figure 1. Large forest fires in Finland during 1996–2014 as classified on the basis of fire size.

fires (approximately 0.6 % of all forest fires) burned 10 ha or more forest. Hereafter, we refer to these fires as large forest fires. The largest forest fire in the database burned 200 ha of forest in Tammela in 1997 but most of the large forest fires burned only 10–25 ha (Fig. 1).

2.2 Climate data

In order to build a relationship between the fire data and prevailing weather conditions, we used gridded daily weather data covering Finland over the period 1996–2014 for which the fire data existed. Air temperature (daily mean, maximum and minimum) and daily mean relative humidity at a height of 2 m, as well as precipitation, observed by the Finnish Meteorological Institute weather observation network were interpolated onto the same high-resolution 0.1° × 0.2° grid with the fire data by applying kriging with external drift (Aalto et al., 2013). Because the quality of wind speed observations did not support the creation of a homogenous gridded daily data set for Finland, we used coarser daily wind speed data from the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis (Dee et al., 2011). These data were provided on a regular 0.75° × 0.75° grid and bilinearly interpolated onto the same 0.1° × 0.2° grid with the above-mentioned other variables.

To estimate the effects of changing climate on the forest-fire risk, we used daily data from five CMIP5 models (Table 1). The models were chosen on the basis of their skill to simulate the present-day average monthly temperature and precipitation climatology in northern Europe and the availability of all required variables on a daily timescale. Our study period consisted of the years 1980–2099 and historical simulations until 2005 were combined with simulations under RCP4.5 and RCP8.5 emission scenarios (van Vuuren et al., 2011) for the period 2006–2099. Because climate model outputs are often biased high or low in relation to the observed climate (e.g. Cattiaux et al., 2013), and in addition, presented on a relative coarse grid, we performed a combined statistical downscaling and bias correction on the modelled daily values before calculating the forest-fire-risk index. We performed the downscaling onto the Finnish 0.1° × 0.2° grid by applying a quantile-mapping technique using smoothing (Räisänen and Räty, 2013; Räty et al., 2014).

Figure 2 illustrates projected changes in climate variables in our data set. The mean daily maximum temperature of the forest-fire season is projected to increase in Finland by 1–3 °C for the period 2010–2039, 2–6 °C for the period 2040–2069, and 2–8 °C for the period 2070–2099, relative to the baseline period 1980–2009 depending on the scenario and model. The projected change is greater in RCP8.5 than in RCP4.5, although there is a considerable amount of variability in the rate of change among different models for temperature and other variables. As for temperature, the projected change is uniformly positive for precipitation. April–October precipitation is likely to increase in Finland by about 20 % by the end of the twenty-first century. For relative humidity, the projections indicate a decrease by 0–6 percentage points within the present century. For wind speed, the projected changes vary around 0 % with considerable inter-model variation for all periods under both scenarios. Regionally, both temperature and precipitation are projected to increase more in northern than in southern Finland (not shown). Moreover, the projected increases in temperature and precipitation are in general larger for early and late forest-fire season than for the midsummer months. Consequently, in the southern and

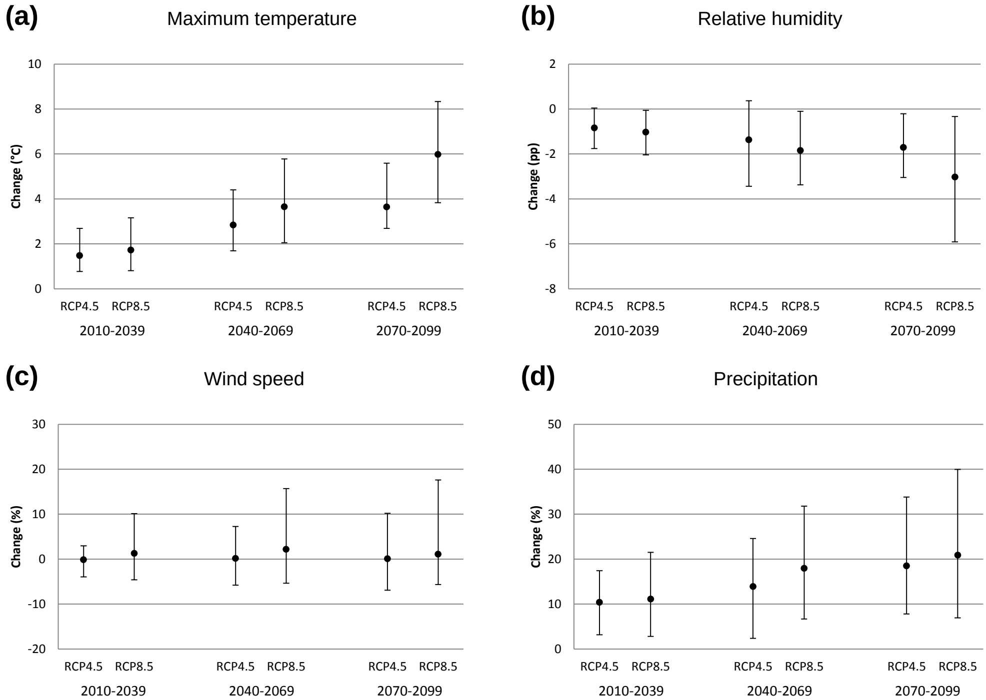

Figure 2. Projected changes in April–October mean daily maximum air temperature at 2 m **(a)**, daily average relative humidity at 2 m **(b)**, daily average wind speed at 10 m **(c)**, and total precipitation **(d)** compared to the period 1980–2009 and averaged over the whole of Finland. Dots indicate the multi-model mean change and whiskers extend to the maximum and minimum projections.

eastern parts of the country, precipitation may even decrease between June and August.

2.3 Forest fire risk assessment based on the fire weather index system

We assessed the forest-fire risk by applying the FWI system following Van Wagner and Pickett (1985). In the FWI system, three soil moisture codes are calculated on a daily basis based on air temperature, relative humidity, and wind speed observations at local noon and the total precipitation sum of the preceding 24 h. Affected by wind speed, these codes are then converted into three fire behaviour indices. The final FWI rating is a dimensionless quantity indicating the likely intensity of fire. The FWI rating can be further converted into daily severity rating (DSR) according to

$$\mathrm{DSR} = 0.0272 \times \mathrm{FWI}^{1.77}. \quad (1)$$

The DSR emphasizes higher FWI values through the power relation and reflects the expected efforts required for fire suppression more accurately than FWI. The DSR can be averaged over time to give the seasonal severity rating (SSR):

$$\mathrm{SSR} = \sum_{i=1}^{n} \mathrm{DSR}_i / n, \quad (2)$$

where DSR_i is the DSR value for the ith day, and n is the total number of days. The DSR averaged over a 1 month period is referred to as the monthly severity rating (MSR).

Because climate model data were provided as daily mean values, we converted the daily means of relative humidity and wind speed to correspond to the afternoon values better and took advantage of available daily maximum temperature data by using the bias-corrected daily maximum temperatures for calculating the FWI. The bias-corrected precipitation sums were used unaltered since 24 h precipitation sums are intended to be used in the FWI system. In converting the daily means of relative humidity into afternoon values, we used daily maximum temperatures and assumed specific humidity to stay constant throughout a day. In the case that this lead to night-time supersaturation according to the bias-corrected daily minimum temperatures, the moisture content of air at night was reduced to give a maximum relative humidity of 100 % at the time of the minimum temperature. The moisture content of air at the time of maximum temperature was correspondingly increased so that the daily mean specific humidity remained unaltered. To reflect the diurnal cycle in wind speed, we simply multiplied the bias-corrected daily mean wind speeds by 1.2, as on average, wind speed peaks in the early afternoon in phase with diurnal cycle of near-surface air temperature. This was based on 30 years (1980–2009) of meteorological observations from four locations (Vantaa, Jokioinen, Jyväskylä, and Sodankylä) across Finland, which

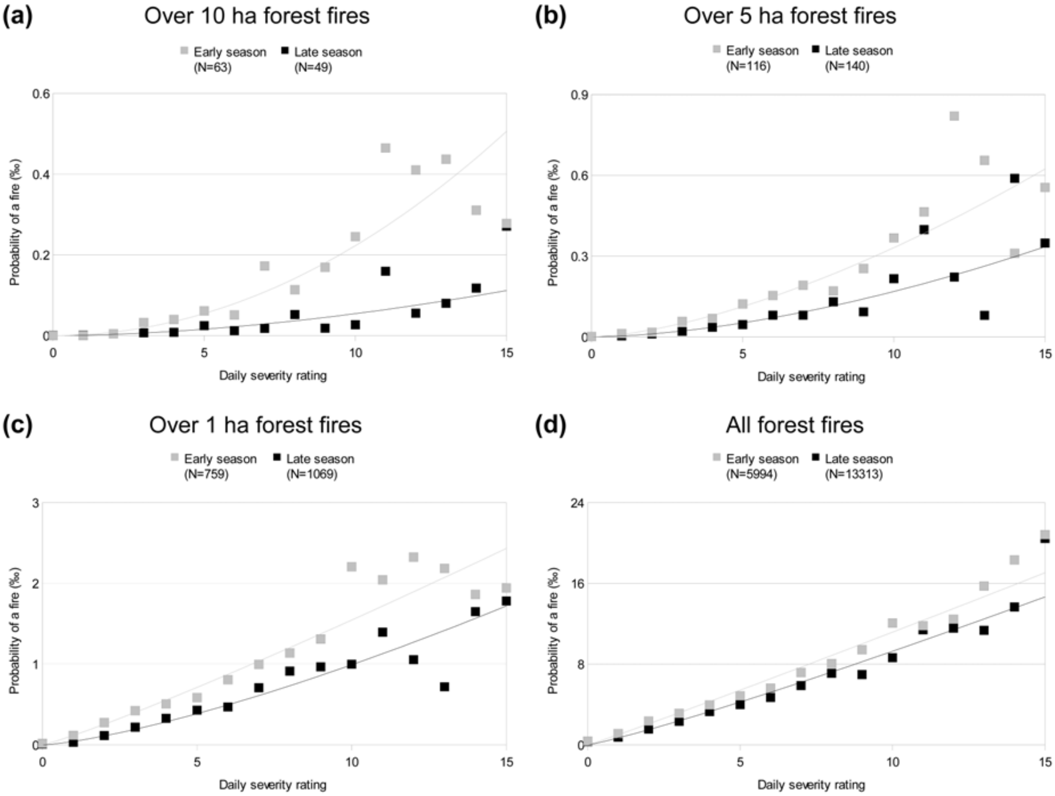

Figure 3. The relationship between daily severity rating (DSR) and occurrence of forest fires of different size in Finland during 1996–2014, performed separately for the early (effective temperature sum below 250 °C days; grey squares) and late season (effective temperature sum above 250 °C days; black squares). **(a)** Forest fires over 10 ha (i.e. large forest fires). **(b)** Forest fires over 5 ha. **(c)** Forest fires over 1 ha. **(d)** All forest fires. The numbers of fires in each class is shown as well.

showed that on average, wind speed exceeds the daily mean in the afternoon by about 20 %. The same set of observations also showed that the procedure of transforming daily mean relative humidities into afternoon values was valid and produced correct results, on average.

2.4 Regression models for fire-danger estimations

In order to estimate the impact of climate change on fire danger, we first compared the gridded DSR values with the information on locations of forest fires during 1996–2014. As the ignition probability with the same FWI value varies considerably between different stages of seasonal vegetation development (Tanskanen and Venäläinen, 2008), the inspection was performed separately for the early and late season (Fig. 3). We used the early season probability from the beginning of the growing season until the effective temperature sum reached 250 degree days when understorey vegetation is fully developed (Tanskanen and Venäläinen, 2008). In the current climate, this happens over most of Finland typically during the first half of June. Then, the late season probability was used until the end of October when the forest-fire season in Finland is virtually over (Tanskanen and Venäläinen, 2008). The commencement of the growing season was annually defined to occur on a date, which after daily mean temperature, remained above 5 °C on average. In general, the ignition probabilities were higher during the early season than the late season. Moreover, the larger the fires that were inspected, the larger this difference was. Among the tested relations (linear relation, exponential relation, and power-law relation), the ignition probabilities best followed the power-law relation as a function of DSR. For large forest fires (i.e. fires over 10 ha), the occurrence probability in a single grid cell in a given day as a function of DSR was estimated via the power relation:

$$
\begin{aligned}
&P(\mathrm{DSR}) = 0, \text{ when DSR} = 0 \\
&P(\mathrm{DSR}) = a \times \mathrm{DSR}^b, \text{ when } 0<\mathrm{DSR} \leq 15 \qquad (3)\\
&P(\mathrm{DSR}) = a \times 15^b, \text{ when DSR}>15.
\end{aligned}
$$

For the early season, we used the coefficients $a = 0.002114452978079$ and $b = 2.02257786261162$ and for the late season $a = 0.000919759277827$ and $b = 1.77233673026624$. By summing the probabilities over the whole of Finland (excluding the Åland Islands) and the fire season, we modelled the annual number of large forest

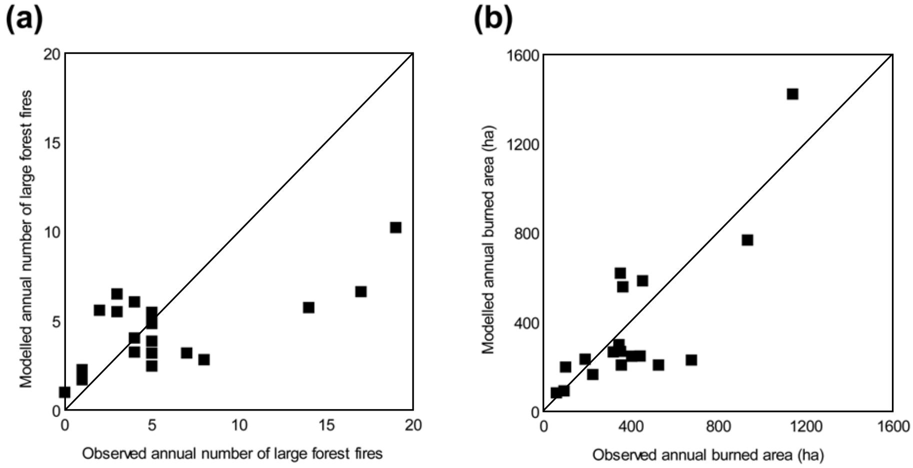

Figure 4. **(a)** Modelled annual number of large forest fires as a function of observed annual number of large forest fires in Finland during 1996–2014. **(b)** As in **(a)** but for annual burned area.

Table 2. Coefficients a and b used in Eq. (4) to estimate the total burned area by month as a function of MSR averaged over the whole of Finland. R^2 is the coefficient of determination.

Month	a	b	R^2
April	69.58	1.97	0.54
May	52.96	1.07	0.28
June	6.85	2.71	0.67
July	7.67	2.58	0.83
August	10.33	2.61	0.56
September	16.37	2.97	0.67
October	7.96	1.23	0.42

fires in Finland. As only 0.2 % of considered days (and 8 % of large forest fires) showed a DSR above 15, we assumed the fire probability to stay constant when the DSR was above 15, as it was hard to say whether the same power relation still applies with such high DSR values. Nevertheless, we repeated all of our calculations, assuming that the power relation would hold with DSRs above 15 and the estimated numbers of large forest fires were only limitedly increased because high DSRs occur relatively seldom.

A similar power relation was created to estimate the annual burned area in Finland based on MSRs averaged over the whole of Finland from April to October:

$$A(\mathrm{MSR}) = a \times \mathrm{MSR}^b, \quad (4)$$

where A is the monthly burned area in hectares. We defined the coefficients a and b separately for each month (Table 2) and estimated the annual burned area by summing the estimated burned areas in each month.

Performance of the regression models is illustrated in Fig. 4 and the statistics for model validation are summarized in Table 3. In general, the regression model for burned area showed higher correlation with observations than the model for the number of large forest fires. In addition, the highest annual peaks in the number of large forest fires are underestimated, leading to a negative mean bias error. The nonparametric Spearman's rank correlations between the models and observations were weaker than the parametric Pearson's correlations. Nevertheless, the Spearman's correlation for burned area was still statistically significant at 1 % level.

2.5 Data analysis

First, we studied the distribution of large forest fires in Finland and the fire activity with regard to population density based on the fire statistics during 1996–2014. We assumed that no significant impact on the fire regime is caused due to differences in fuel amount or type because forest fuels are relatively similar throughout Finland with the exception of the tundra vegetation in northernmost Lapland above 68° N (Reinikainen et al., 2000). Then, we used Eqs. (3) and (4) to estimate the number of large forest fires and burned area in Finland until 2099 by utilizing the climate model data.

3 Results

3.1 Fire regime in Finland

The distribution of large forest fires in Finland during 1996–2014 is shown in Fig. 5a along with population density. The average size of forest fires in Finland steadily decreases with increasing population density (Fig. 5b), while the population density tends to strongly decrease towards the north. Hence, although the occurrence of forest fires has a strong positive correlation ($R^2 = 0.85$) with population density on a regional scale (Fig. 5c), this dependency is largely absent when con-

Table 3. Statistics for the model validation over the period 1996–2014.

	Pearson correlation	Spearman correlation	Mean bias error	Root-mean-square error
Large forest fires	0.67**	0.39*	−1.43	4.25
Burned area	0.81***	0.58**	−34.34	184.87

Asterisks denote statistical significance (* $p<0.1$; ** $p<0.01$; *** $p<0.001$).

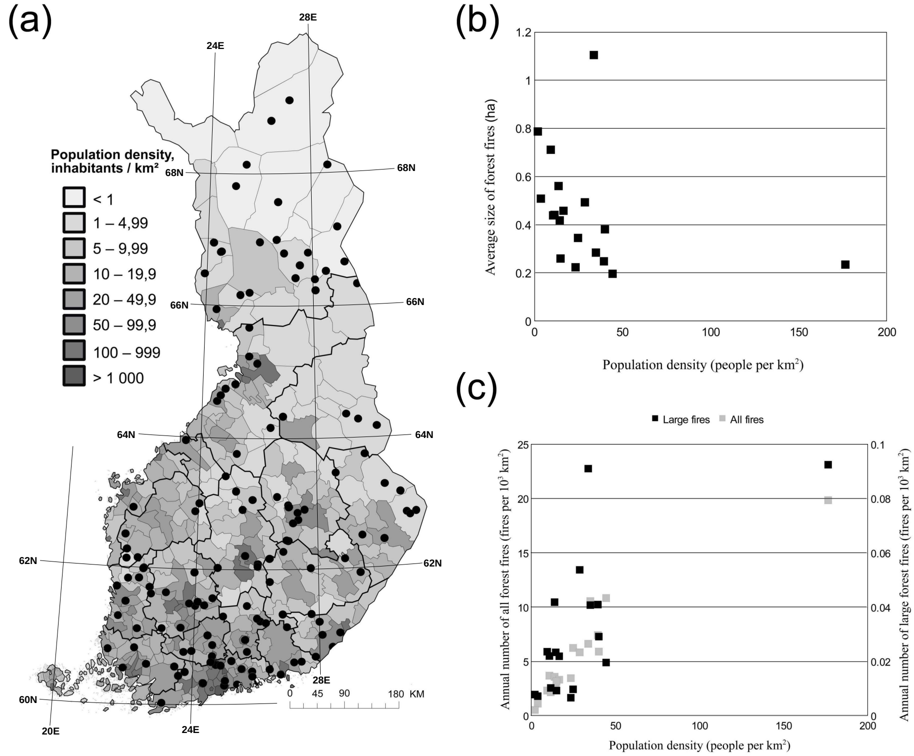

Figure 5. (a) Locations of large forest fires in Finland during 1996–2014 along with population density by municipality. **(b)** Average size of forest fires in Finland by region during 1996–2014 as a function of population density. **(c)** Annual mean number of all forest fires (grey squares) and large forest fires (black squares) per 10^3 km^2 in Finland by region during 1996–2014 as a function of population density.

sidering large forest fires. This is one reason why we decided to use 10 ha as a threshold for large forest fires.

Figure 6 shows MSRs based on observational weather data during 1996–2014 along with monthly burned forest areas. As seen in Table 2, the burned area correlates best with MSR in July and worst in May. In general, variations in the annual burned area reflect variations in SSR fairly well. The Pearson product-moment correlation coefficient between these two variables proved to be as high as 0.75 during 1996–2014. Nevertheless, when the annual burned area is estimated on the basis of MSRs by using Eq. (4), the correlation with the actual burned area is even higher (0.81; Table 3).

Annual modelled and observed numbers of large forest fires and burned area in Finland during 1996–2014 are displayed in Fig. 7. As can be expected based on the positive correlations in Table 3, the modelled fire activity follows the observed fire activity well enough to depict the main temporal variations. The highest modelled annual peaks in the number of large forest fires are underestimated largely due to weak correlation between the fire weather and occurrence of large forest fires in May. For instance, in 1997 and 2008, two years with relatively many large forest fires, all large forest fires occurred before mid-June and most of them in May. However, May and early June also displayed similarly dry fire weather conditions in 1999, 2000, and 2002; but only a few large forest fires occurred during these years.

Classification of large forest fires based on the reported ignition source reveals interestingly that early season fires are almost entirely human-induced; whereas in July, most large forest fires are ignited by a lightning strike (Fig. 7c). Outstandingly common human-caused large forest fires are in May and early June. The large majority of all human-caused large forest fires in Finland during 1996–2014 occurred during this relatively short period. At that time of year, the large

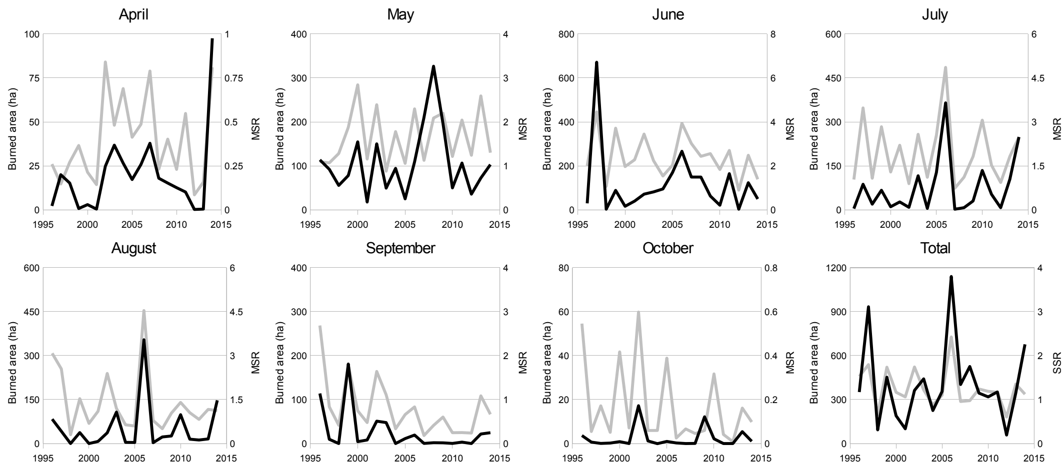

Figure 6. Burned forest area (black lines) in Finland by month and monthly severity rating (grey lines) averaged over the whole of Finland during 1996–2014.

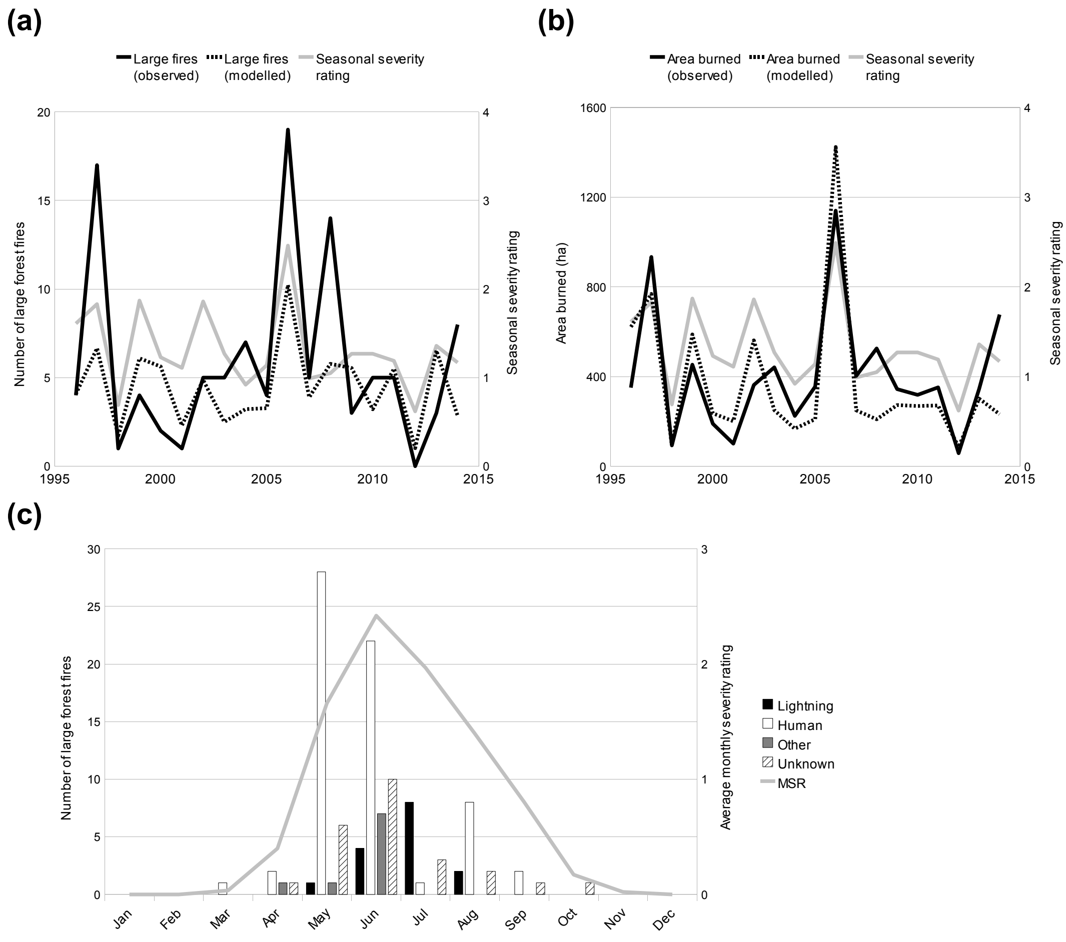

Figure 7. (a) Annual observed (solid black line) and modelled (dashed black line; based on Eq. 3) numbers of large forest fires in Finland during 1996–2014, as well as the annual April–October seasonal severity rating averaged over the whole of Finland (grey line). **(b)** Annual observed (solid black line) and modelled (dashed black line; based on Eq. 4) area burned in Finland during 1996–2014, as well as the annual April–October seasonal severity rating averaged over the whole of Finland (grey line). **(c)** Nationwide average of monthly severity rating (MSR) in Finland during 1996–2014 (grey line) and monthly distribution of large forest fires in Finland within the same period, divided by the source of ignition (bars).

Table 4. Proportions (in %) of forest fires of different sizes, divided according to the daily severity index (DSR) classes in Finland during 1996–2014.

DSR	<1 ha	1–5 ha	5–10 ha	10–20 ha	>20 ha
< 1	96.4	3.2	0.2	0.2	0.0
1–5	90.8	8.2	0.6	0.3	0.1
5–10	87.6	10.5	1.1	0.4	0.4
> 10	89.2	8.1	1.2	0.7	0.8

fires tend to be often caused by escalated prescribed burning or the burning of rubbish. These activities are not practised anymore later in summer.

The average size of forest fires in Finland increases with increasing severity of prevailing fire weather. The large majority of all forest fires still burn less than 1 ha of forest with high DSR values, but the share of large forest fires (we recall that with large forest fires, we refer to all forest fires larger than 10 ha) increases from 0.2 to 1.5 % when the DSR increases from below 1 to over 10 (Table 4).

3.2 Projected climate change impact on the forest-fire risk

The SSR averaged over the April–October period likely already increased during the early twenty-first century, and by the period 2070–2099, the nationwide multi-model mean change exceeds 100 % under the RCP8.5 scenario (Fig. 8a). However, among different model projections, the increase varies between 28 and 200 %. For the number of large forest fires, the projected change is slightly larger than for SSR (Fig. 8b). For instance, under the RCP8.5 scenario the range for the projected increase from 1980–2009 to 2070–2099 is from 54 to 238 %. For the burned area, future estimates have a huge variability among different model projections (Fig. 8c). Already by the period 2010–2039, the projected change varies approximately between 5 and 200 %. By the period 2070–2099, the burned area is projected to increase under the RCP8.5 scenario by 35–1271 %, depending on the model, and under the RCP4.5 scenario by 56–441 %. However, as the burned area has been small during recent years, even a single fire comparable in size to the Västmanland wildfire in Sweden in 2014 would burn about twice as much forest area than was burned in Finland during the years 1996–2014 in total. Hence, occurrence of only a couple of conflagrations could lead to an increase of hundreds of percent in the burned area. For all statistics, the projected multi-model mean change and the range among different model projections are smaller under the RCP4.5 than RCP8.5 scenario.

Regionally, the forest-fire danger is projected to increase rather similarly throughout Finland (Fig. 9). Under the RCP8.5 scenario, multi-model mean SSR averaged over the April–October period increases in the south from about 2–3

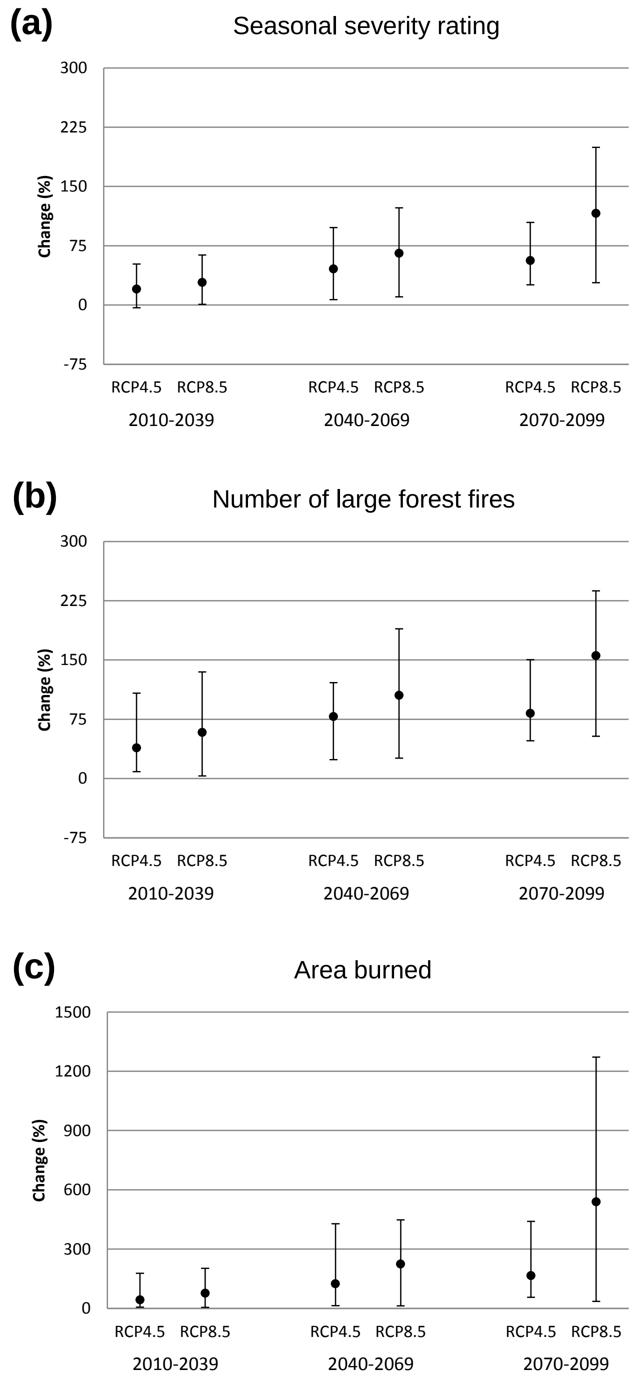

Figure 8. Projected changes in April–October seasonal severity rating averaged over the whole of Finland **(a)**, in the number of large forest fires in Finland **(b)**, and in the area burned **(c)** compared to the period 1980–2009. Dots indicate the multi-model mean change and whiskers extend to the maximum and minimum projections.

Table 5. The 90th, 50th, and 10th percentiles of multi-model mean annual number of large forest fires in Finland, excluding the Åland Islands. The range in the number of modelled large forest fires among the model projections is shown in parentheses.

	RCP4.5 1980–2009	RCP4.5 2010–2039	RCP4.5 2040–2069	RCP4.5 2070–2099
90th percentile	11 (6–18)	12 (10–15)	15 (13–18)	14 (12–16)
50th percentile	5 (4–6)	6 (5–7)	9 (5–10)	9 (8–9)
10th percentile	2 (1–2)	3 (2–4)	5 (2–6)	4 (3–6)
	RCP8.5 1980–2009	RCP8.5 2010–2039	RCP8.5 2040–2069	RCP8.5 2070–2099
90th percentile	9 (7–11)	15 (11–24)	16 (12–20)	18 (11–21)
50th percentile	4 (4–5)	7 (4–10)	10 (6–14)	12 (8–16)
10th percentile	2 (1–2)	3 (2–4)	5 (4–8)	7 (4–12)

to 4–6 and in the north from about 1 to 2 until the end of the twenty-first century; i.e. it approximately doubles.

Moreover, the fire danger is projected to increase both during the driest and wettest summers but in relative terms, the number of large forest fires is expected to increase most in the summers that express a relatively small number of large fires (Table 5). In spite of large inter-model variability, the number of large forest fires during a typical year in the late 21st century is expected to be close to what it was was during the recent years that experienced the highest number of large forest fires (e.g. 1997, 2006 and 2008). Similarly, the easiest future fire seasons would be comparable to the current average fire seasons.

4 Discussion and conclusions

4.1 Evaluation of methodology

In this study, we used statistically downscaled climate model simulations to evaluate the impact of climate change on the number of large fires and total burned area in the boreal forests of Finland. In assessing the fire risk, we applied the FWI system, and the statistical downscaling was performed with the quantile-mapping technique. Quantile mapping has proven to be among the best-performing empirical bias-correction methods for temperature (Räisänen and Räty, 2013) and precipitation (Räty et al., 2014) throughout the probability distribution and it has been suggested the most in recent studies (e.g. Teutschbein and Seibert, 2012). Quantile mapping has also been previously successfully applied for correcting relative humidity and wind speed simulations (Wilcke et al., 2013). Moreover, Yang et al. (2015) used a rather similar approach for correcting regional climate model output in order to assess forest-fire risk in Sweden. However, the method is still by no means perfect. Where the local differences between simulated and observed climates are fairly large, the downscaling technique is less likely to yield accurate results. In Finland, these areas include many coastal regions and, in addition, northernmost Lapland, where the relatively scarce station density is compounded with com-

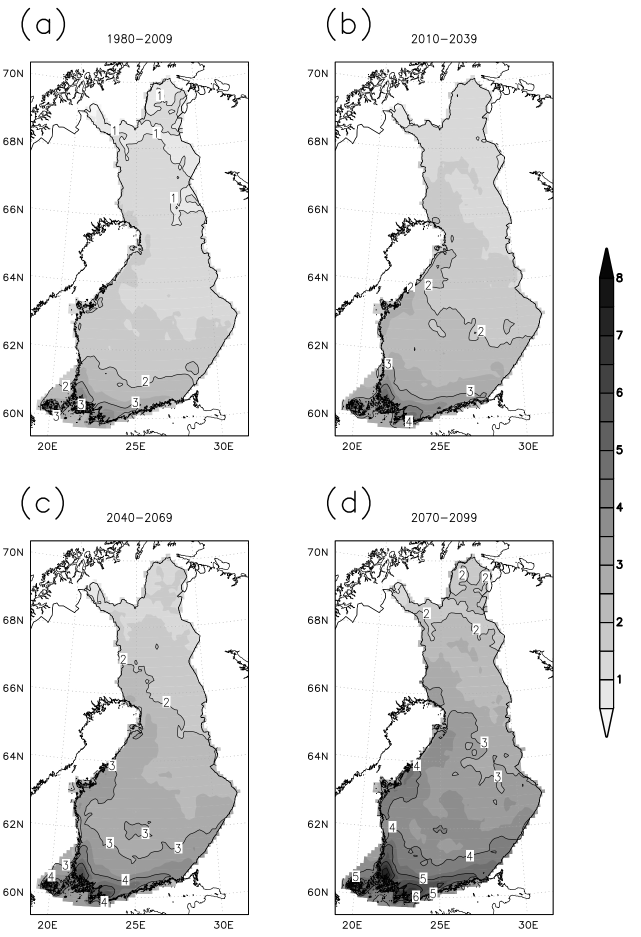

Figure 9. Projected multi-model mean for the April–October seasonal severity rating (SSR) in 1980–2009 **(a)**, 2010–2039 **(b)**, 2040–2069 **(c)**, and 2070–2099 **(d)** under the RCP8.5 scenario.

plex topography. One shortcoming of the quantile-mapping method is that averaging the downscaled time series back to the original resolution leads to overestimation of extreme values if the variable in question has much small-scale variability (Maraun, 2013). This holds particularly for precipitation. This effect is only visible for the area-averaged time series, and in the present study, it probably somewhat increased the inter-annual variability in the fire weather projections.

The FWI system applied in fire-risk estimation was initially developed empirically for Canadian boreal conditions, but it has become widely implemented in other countries around the world as well. Eventually, the FWI system has been suggested as the basis for a global early warning system for wildland fires (de Groot et al., 2006). Comparison of FWI to the forest-fire index used operationally in Finland revealed that the two indices perform similarly in Finnish conditions (Vajda et al., 2014).

The developed regression models for estimation of the number of large forest fires and burned area have marked uncertainties. Firstly, the period consisting of information on fire locations and used in developing the regression models is fairly short, only 19 years. Secondly, it is uncertain that a similar relationship between fire weather and fire activity would still hold in the future if the fire weather turns much more severe. However, as most of large forest fires occur when the fire danger is only moderately high, the change in the most extreme conditions has less relevance because those situations will, in any case, occur relatively rarely. Thirdly, weather explains only a part of the variability in fire activity. Our results suggest that roughly about half of the variability in the annual burned area can be explained by variations in MSRs, but in the long term, other factors may be more important.

The use of the DSR instead of FWI ameliorated our results: the correlation between annual burned area and SSR (~ 0.75) was larger than reported by Venäläinen et al. (2014) between annual burned area and seasonal mean FWI (~ 0.60) in Finland. By taking into account the seasonal variations in the correlations between fire activity and fire-danger indices, limited improvements were achieved in the performance of our regression models; though this is also one source of uncertainty. Currently, most large forest fires in Finland occur within a relative short period in May and early June as a result of human activities, often including prescribed burning and the burning of rubbish. It may have an impact on the fire activity whether these activities are still conducted during the same time of year in the future or whether they will be preponed as the commencement of the growing season is projected to take place earlier in a warmer climate (Ruosteenoja et al., 2011). In addition, the correlation between fire activity and fire danger was poorest during this time of year, indicating that the use of fire by humans is probably reduced while the fire danger is high. Later in summer, when lightning is more important cause of large forest fires, fire-danger indices correlate much better with the observed fire activity. Consequently, the projected increase in the burned area is, by a large part, caused by the projected increase in fire danger during midsummer and late summer.

4.2 Evaluation of main results

In accordance with previous studies (Kilpeläinen et al., 2010; Lehtonen et al., 2014b; H. M. Mäkelä et al., 2014), we found that in response to climate change, the forest-fire risk in Finland will increase with a high probability. In these previous studies, the projected change in fire danger was converted into the change in the number of days expressing a high forest-fire danger. Because extreme conditions are more relevant with regard to fire management efficiency, we estimated the climate change impact on potential large-scale forest fires and burned area. Our results suggest that the number of large forest fires could easily double by 2100, but there is large variability in the projected change among different models and also between the two emission scenarios considered here. Hence, the change can be, in the worst case, even larger. This large inter-model variability is already evident with the subset of five different GCMs used in this study. Within a larger model set, this variability would probably be even larger. To exemplify this, based on results of a single climate model, Yang et al. (2015) estimated that northern Sweden, which is in close proximity to Finland, would face lower fire risk in the future than today. It was mainly because in their simulation, climate was projected to become more humid, while our projections indicated either drier future conditions or little change in relative humidity. In general, the large uncertainty ranges related to the fire-danger projections reflect that uncertainties related to changes in temperature, precipitation, wind, and humidity climates all add uncertainty to the estimation of forest-fire danger. Possible changes in wind climate are particularly important because the FWI rating has been found to be most sensitive to wind speed (Dowdy et al., 2010) and as the multi-model mean change for wind speed is close to zero, it is uncertain whether the actual change will be positive or negative.

The estimates given for burned area are highly uncertain, mostly because the occurrence of only a few conflagrations would increase the burned area from the present level by hundreds of percent. Nevertheless, the likely increase in the number of large fires driven by general increase in the fire danger increases the probability that some of these fires would escalate to conflagrations. It is thus of the utmost importance to suppress the fires as quickly as possible, which may prove to be problematic if multiple fires are ignited within a short time in isolated locations.

Considering the multi-model mean, the present projections for the number of large forest fires and burned area clearly show larger increases than previously estimated for the increase in the number of fire-danger days. This is partly because a larger portion of all fires spread into large fires when fire weather becomes more severe. An additional explanation is that the RCP8.5 scenario is a more extreme climate change scenario than any of the scenarios used in the previous studies which applied the Special Report on Emission Scenarios (SRES) (Nakićenović et al., 2000). While based on the multi-model mean under the high-emission SRES A2 scenario, summer temperatures in Finland were projected to increase by about 3 °C by the end of the present century (Giorgi and Coppola, 2009); this increase is almost 5 °C in the RCP8.5 scenario (Cattiaux et al., 2013). Moreover, among the models involved in this study, the warming is, on average, slightly larger. Actually, the projected summertime warming in Finland under the RCP4.5 scenario corresponds closely to that under the SRES A2 scenario. For wind speed, relative humidity, and precipitation, the projected changes among the models involved were, on average, rather similar to projected changes from the multi-model means under the SRES scenarios (Gregow et al., 2012; Ruosteenoja and Räisänen, 2013; Lehtonen et al., 2014a).

The impact of climate change on the annual burned area has been previously estimated with the FWI system in North America (Flannigan et al., 2005; Balshi et al., 2009) and in the Mediterranean region (Amatulli et al., 2013). Flannigan et al. (2005) suggested that in Canada, the annual burned area could approximately double by the end of this century, and an even greater increase was projected by Balshi et al. (2009). Recently, Migliavacca et al. (2013) estimated the future burned area in Europe by using a land–atmosphere model that computes the probability of fire occurrence as the product of three terms: the probability related to biomass availability, the probability conditioned on the moisture, and the probability of ignition. They demonstrated that a reduction in productivity reduces the increase in fire activity over semiarid regions, but this is unlikely to happen in northern Europe where forest productivity and biomass stock are projected to increase under a warming climate (Kellomäki et al., 2008; Dury et al., 2011), increasing the forest-fuel load. In northern Europe, Migliavacca et al. (2013) found temperature to be the most important driver of fire activity. For burned area, their results curiously showed an abrupt doubling of the annual burned area in northern Europe around 2010 and no coherent change after that under the modest SRES A1B emission scenario.

Our results indicating substantial increase in the number of large forest fires and burned area in Finland due to a warming climate are generally quantitatively similar with the findings of the above-mentioned studies. The projected increase in fire danger is essentially due to the reduction in forest-fuel moisture content. Previously, Dai (2013) has shown that CMIP5 models consistently project soil moisture to decrease over all of Europe. In Finland, the drying of soil is mostly a result of the increase in evaporative demand exceeding the increase in precipitation. In the future, the fire season is also expected to start earlier because of earlier snowmelt (Räisänen and Eklund, 2012) and earlier commencement of the growing season (Ruosteenoja et al., 2011). In autumn, a considerable lengthening of the fire season is not probable because air humidity increases towards winter due to a shortening of the day length.

Tanskanen and Venäläinen (2008) had previously demonstrated that there are three peaks in annual fire activity in Finland: the first in late May and early June, the second after mid-July, and the third in September. They did not directly inspect the ignition sources of fires but hypothesized that the second peak may be associated with lightning, and the last peak, mainly consisting of small-scale fires, would occur because as a result of the open season for elk hunting, as well as various gathering activities, people fill the forests and light campfires. Consistent with their hypothesis, we showed that most large fires in July are ignited by lightning strikes. Moreover, the annual course of lightning-ignited large forest fires follows the annual lightning activity closely, with a peak in July (A. Mäkelä et al., 2014). The first and most prominent peak in fire activity in late May was considered surprising by Tanskanen and Venäläinen (2008) because May had previously been considered a marginal part of the fire season. They assumed that the majority of fires originating from silvicultural slash burning of cured vegetation and rubbish are likely to occur during this time of year. Again, our results confirm this assumption: the large fires in May and early June are almost entirely human-caused, and mainly because of the above-mentioned activities. Moreover, because humans ignite many more large fires before mid-June than later in summer, the seasonal vegetation development might not be the main reason for the higher ignition probabilities in the early season found in fire statistics.

4.3 Conclusions

The impact of climate change on forest-fire danger in Finland with emphasis on large-scale fires and model-based uncertainty was studied using the statistically downscaled and bias-corrected daily output of five CMIP5 models. The regression models for estimating the number of large forest fires and burned area were constructed based on the fire statistics covering the years 1996–2014. Our results show that the number of large forest fires may double or even triple by the end of this century but above all, the projections show large inter-model variability. Because of several uncertainties related to this study, the results should be considered to be only approximate; though they highlight the large uncertainty in the rate of the projected increase of forest-fire danger, which is moreover only partly covered by climatological factors considered in this study.

Our results largely confirmed the previous presumptions of Tanskanen and Venäläinen (2008) about the ignition sources of fires at different times of the year. Human-caused large fires are greatly over-represented in late May and early June; whereas in July, lightning ignites the majority of large fires. We also showed that the correlation between fire activity and fire weather indices is poorest in May when humans ignite more large fires than during any other month. However, our results did not indicate that population density is a key driver in the occurrence of large forest fires in Finland. That is because although the number of forest fires steadily increases with increasing population density, the average size of fires simultaneously decreases.

Climatological conditions do not prevent conflagrations from occurring in Finland. An increase in fire danger increases the proportion of large-scale fires because the fire managers have less time to suppress the fires if the conditions for vigorous spread of fire are favourable. Even a single conflagration could burn more forest area than has been typically burned within 1 decade in Finland during the last half a century. Our results suggest that the probability of such an event occurring will increase. For the highest projections of burned area to become realized, some fires comparable to the Västmanland wildfire would virtually be required to take place during the present century.

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