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Discussions

Risk for 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 the number of large forest fires (over 10 ha fires) and burned area in Finland. For this purpose, we utilized a strong relationship between fire occurrence and the Canadian fire weather index (FWI) during 1996–2014. We used daily 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. 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. Our results also reveal substantial inter-model variability in the rate of the projected increase in forest-fire danger. We moreover showed that the majority of large fires 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 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 ten 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 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 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 escape to large fires that pose a risk for devastating-scale conflagrations.

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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 one hectare. Fire survey flights contribute to early detection of ignited fires and the dense forest road network in Finland aids fire fighters to reach and suppress the fires. During the 19th century and early 20th century, large forest fires were still not uncommon in Finland. Back then, the average size of forest fires was in many years over 50 ha 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 19th 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 Finland, the largest forest fire during the recent decades burned 20 000 ha of forest in Lapland along the Russian border in 1960 and the same fire burned an additional 100 000 ha of forest in the Russian side of the border (Vajda and Venäläinen, 2005).

In determining the risk of forest fires, weather and climate play a key role along with fuel amount. High temperatures accompanied by low relative humidity and strong winds enhance evaporation and drying the soil and further 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), but although human activities are responsible for most forest fires, weather makes the conditions favorable 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 20th century has been attributed to increased drought in the area (Xiao and Zhuang, 2007).

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In response to global warming, the forest-fire risk is generally projected to increase in the circumboreal region which may hamper the effectiveness of fire management (e.g. Flannigan et al., 2009). Focusing on Finland, Kilpeläinen et al. (2010) predicted that the average annual number of forest fires could increase by about 20 % during the present century. Similarly, Lehtonen et al. (2014b) estimated that the number of days with elevated forest-fire risk would increase in Finland by 10–40 % by 2100 depending on the applied greenhouse-gas scenario. In both studies, ensemble monthly means of several general circulation model (GCM) simulations were used to project the future climate and anticipated change in forest-fire danger. H. M. Mäkelä et al. (2014) used a multiple regression model to estimate the number of forest fire danger days in Finland under the changing climate based solely on the anomalies of summer mean temperature and precipitation. They applied probabilistic climate projections (Harris et al., 2010) based on simulations with a single GCM. Their results showed a high probability for the number of forest fire danger days to increase, the relative increase being largest in northern Finland.

The above-mentioned earlier studies have mainly concentrated on the effect of changes in climatic mean conditions to the forest fire potential and the aspect of climate change impact on large fires having major socioeconomic and ecological impacts has been missing. Moreover, in spite of continuous development of climate models, the range of model uncertainty has not considerably decreased after the 1990s (Räisänen and Ylhäisi, 2014). Different models simulate somewhat different changes in climate in response to the same radiative forcing and with lead times of a few decades, this model uncertainty can account for more than half of the total uncertainty related in climate projections (Hawkins and Sutton, 2009). Hence, there exists a clear need to update the fire danger assessment by using several models instead of the usually applied multi-model mean approach.

Moreover, in countries like Finland, where forest-based bioeconomy has, in addition to great economic importance, a key role in climate change mitigation, it is particularly important to understand the impact of climate change on the risks affecting forests and

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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 study, our target is to estimate the impact of climate change on the occurrence of large-scale fires and burned area in boreal forests of Finland. The results can be generalized to depict conditions more widely, e.g. in northern Europe and western Siberia. Another specific interest is to explore the uncertainty related to the projected changes. For this purpose, we use daily input from five independent 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 over the period 1980–2099. In this work, modelled values of weather variables are downscaled onto a high-resolution grid covering Finland using the quantile-mapping approach. The use of modelled daily values instead of monthly means makes it easier to take into account potential changes in extreme weather conditions, which are most relevant regarding the forest-fire risk. For instance, changes in the duration of wet and dry spells are not necessarily linked to variations in mean precipitation (Zolina et al., 2013). Furthermore, by comparing the results based on different GCMs we can easily estimate the scale of model uncertainty. 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 and climate data

To study the spatial and temporal occurrence of forest fires in Finland, we used fire data that consisted 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 etc.) of a fire site. The fires occurred in the Åland Islands were not included in the database. In most cases, the locations of fires were given only in municipality level prior to 2005, but thereafter, the exact coordinates of the fire sites were usually provided. In this study, the fires were located onto a $0.1^\circ \times 0.2^\circ$ latitude–longitude grid. Those fires which exact coordinates were not reported were located in the middle of the municipalities where the fires reportedly had occurred. In this study, we excluded all other types of wildland fires except the forest fires. According to the statistics, almost 20 000 forest fires occurred in Finland from 1996 through 2014. 112 of these 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. Because larger fires have occurred during the previous decades, we complemented our fire data with those fires that burned 200 ha or more forest after the 1950s and for which adequate information about the prevailing meteorological conditions was available (Table 1). We moreover included into our analysis the Västmanland wildfire that occurred in Sweden in 2014 as this fire recently demonstrated the possibility for devastating-scale fires in conditions similar to Finland. For calculating the fire weather conditions related to these conflagrations, we used weather data from selected stations located near to the fire sites.

In order to build a relationship between the fire data and prevailing weather conditions, we used high-resolution gridded daily weather data covering Finland over the period 1996–2014 for which the fire data existed. 2 m temperature (daily mean, maximum and minimum), mean 2 m relative humidity and precipitation observed by the Finnish Meteorological Institute weather observation network were interpolated onto the same $0.1^\circ \times 0.2^\circ$ grid with the fire data following the methodology of Aalto et al. (2013). We moreover used mean wind speed data from the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis (Dee et al., 2011). This data was provided on a regular $0.75^\circ \times 0.75^\circ$ grid and bilinearly interpolated onto the same $0.1^\circ \times 0.2^\circ$

grid with other variables. Coarser resolution data for wind speed was used because the quality of wind speed observations did not support the creation of homogenous, high-resolution gridded daily data set for Finland.

To estimate the effects of changing climate on the forest-fire risk, we used daily data for the above-mentioned weather variables from five CMIP5 models (Table 2). 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 time scale. Our study period consisted of years 1980–2099 and historical simulations until 2005 were combined with simulations under RCP4.5 and RCP8.5 emission scenarios for the period 2006–2099. The RCP8.5 (Riahi et al., 2011) is a high-emission scenario leading to a warming of global land areas by almost 5 °C by 2100 on the basis of their multi-model mean (Collins et al., 2013). In the RCP4.5 scenario (Thomson et al., 2011), the radiative forcing stabilizes at 4.5 $W\,m^{-2}$ in 2100 and the warming on global scale is about half of that in the RCP8.5 scenario (Collins et al., 2013). Over the Arctic areas and also in Finland, the projected warming exceeds the global average due to Arctic amplification (Pithan and Mauritsen, 2014).

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 relative coarse grid, we performed a combined statistical downscaling and bias correction to the modelled daily values before calculating the forest-fire-risk index. We applied the quantile mapping bias-correction technique using smoothing. This technique is explained in detail and evaluated for temperature by Räisänen and Räty (2013) and for precipitation by Räty et al. (2014) using regional climate models. We used the same method for correcting the modelled wind speed and relative humidity values. In the quantile-mapping approach, cumulative probability distributions of simulated and observed values of a specific weather variable are compared within the calibration period so that the method fits the simulated distributions to the observed ones. The resulting distribution matches the observed distribution in the calibration period by definition, whereas the shape of the far-future distribution depends on the magnitude of the climate change signal. We performed the bias correction onto the $0.1^{\circ} \times 0.2^{\circ}$ Finnish grid and used as our observational calibration data the gridded weather data over the period 1981–2010.

Projected changes in climate variables in our data set are displayed in Fig. 1. 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 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 21st century. For relative humidity, the projections are fairly robust and the mean relative humidity of the forest fire season is projected to decrease by 0–6 percentage points within the present century. For wind speed, any coherent change is not expected; multi-model mean change is close to 0 % for all periods under both scenarios. Regionally, both temperature and precipitation are projected to increase more in northern than in southern Finland (not shown). In the southern and eastern parts of the country, summertime precipitation may even decrease, particularly during midsummer months.

2.2 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 foul 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 behavior 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:

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

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

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

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

In this study, we used the bias-corrected daily maximum temperatures for calculating the FWI. Daily mean values of relative humidity were converted into afternoon values with the help of daily maximum temperatures by assuming 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 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 showed that, on average, wind speed in afternoon exceeds the daily mean by about 20 %. The same set of observations also showed that the procedure of transforming daily mean relative humidities into afternoon values was a valid and produced correct results, on average. The bias-corrected precipitation sums were used unaltered since 24 h precipitation sums are intended to be used in the FWI system.

For the larger than 200 ha fires, we used actual weather observations made at the stations listed in Table 1 in calculating the fire weather indices. Here, we used directly

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2 m air temperature, 2 m relative humidity and 10 m wind speed values observed at 12:00 UTC and daily precipitation sums in the calculations.

2.3 Regression models for fire-danger estimations

We built regression models for estimating the annual number of large forest fires and total burned area in Finland. To estimate the number of large forest fires, we compared the gridded DSR values with the information on locations of the large 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), we derived the probabilities for large forest fires separately for early and late season. We used the early season probability from the beginning of the growing season until the effective temperature sum reached 250 ° days when understory 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 probabilities were used until the end of October when 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 on average remained above 5 °C. The probability P (in ‰) of a large forest fire to occur in a single grid cell in a given day as a function of DSR was estimated via the power relation (Fig. 2):

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

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

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the Åland Islands) and fire season, we modelled the annual number of large forest fires in Finland.

Based on Eq. (3), the large forest fires are clearly more often ignited with a certain DSR value during the early season compared to the late season (Fig. 2) which accords with findings of Tanskanen and Venäläinen (2008). While low DSRs are much more common than high DSRs, most of large forest fires are still ignited with relative low DSR. Hence, only a few large forest fires had occurred with DSR exceeding 15. We thus assumed the fire probability to stay constant when 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 by assuming the power relation to hold with DSRs above 15 and the estimated numbers of large forest fires were only limitedly increased because that high DSRs occur relatively seldom.

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:

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

where A is the monthly burned area in hectares. We defined the coefficients a and b separately for each month (Table 3) and estimated the annual burned area by summing the estimated burned areas on each month.

The statistics for model validation are summarized in Table 4. 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 non-parametric Spearman's rank correlations between the models and observations were weaker than the parametric Pearson's correlations. For burned area, the Spearman's correlation was still statistically significant at 1 % level. On average, both the modelled annual number of large forest fires and burned area were slightly underestimated.

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2.4 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 the northernmost Lapland above 68° N (Reinikainen et al., 2000). In addition, we studied the fire weather indices related to the conflagrations listed in Table 1. Then, we used the 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

Large forest fires in Finland during 1996–2014 were distributed rather uniformly across the country (Fig. 3a). Nevertheless, they occurred slightly more frequently in southern than northern parts of Finland. Population density in Finland tends to strongly decrease towards the north and the occurrence of forest fires has a strong positive correlation ($R^2 = 0.85$) with population density on a regional scale (Fig. 3c). However, this dependency is largely absent when considering the large forest fires. Admittedly, this is partly because of much smaller total number of large fires in our data set leading to emphasized role of random variation but also because the average size of forest fires steadily decreases with increasing population density (Fig. 3b). Hence, we decided to use the same coefficient in the Eq. (3) throughout the country. We also tested whether the coefficients would change if Finland were divided into smaller sub-regions but the relationship between the fire weather and occurrence of large fires proved to be rather similar across the country. For smaller fires, however, the ignition probabilities with the same DSR value were clearly higher in the south than in more scarcely populated northern Finland.

Figure 4 shows MSRs based on observational weather data during 1996–2014 along with monthly burned forest areas. As seen in Table 3, 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 the Eq. (4), the correlation with actually burned area is even higher (0.81; Table 4).

Annual modelled and observed numbers of large forest fires and burned area in Finland during 1996–2014 are displayed in Fig. 5. As can be expected based on the positive correlations in Table 4, the modelled fire activity quite nicely follows the observed fire activity. Nonetheless, the highest annual peaks in the number of large forest fires seem to be underestimated based on the regression model leading to a negative mean bias error (Table 4). This is 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. On the other hand, May and early June expressed similarly dry fire weather conditions also 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 of large forest fires are ignited by a lightning strike (Fig. 5c). Outstandingly common human-caused large forest fires are in May and early June. A 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 fires tend to be often caused by escaped prescribed burnings or burning of trash. These activities are not practiced anymore later in summer.

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The average size of forest fires in Finland increases with increasing severity of prevailing fire weather. A large majority of all forest fires are still small with high DSR values but the share of large forest fires increases from 0.2 to 1.5 % when DSR increases from below 1 to over 10 (Table 5). However, none of the largest known forest fires during the previous decades were associated with extremely severe fire weather (Table 6). In each case, FWI values were not higher than observed typically at least once every other year. Duff moisture code (DMC) and build up index (BUI) showed in some cases slightly more exceptionally high values. Particularly drought code (DC) was often relatively low but it is because the DC virtually always reaches its maximum value not until in late summer. Based on the observations at Sala weather station, any of the fire weather indices did not show exceptionally high values when the Västmanland wildfire was ignited in the end of July 2014. However, it should be noted that fire weather indices calculated at a single station on the basis of observations at a single time may not be representative to the actual fire site. In addition, in this case, the fire weather indices showed considerably higher values a few days after the ignition when the fire escaped from the fire managers.

3.2 Projected climate change impact on the forest-fire risk

SSR averaged over April–October period likely increases already during the early 21st century and by the period 2070–2099, the nationwide multi-model mean change exceeds 100 % under the RCP8.5 scenario (Fig. 6a). 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. 6b). 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. 6c). 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

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the burned area has been small during the 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 that has been burned in Finland during the years 1996–2014 in total. Hence, occurrence of only couple of conflagrations could lead to increase of hundreds 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. 7). Under the RCP8.5 scenario, multi-model mean SSR averaged over April–October period increases in the south from about 2–3 to 4–6 and in the north from about 1 to 2 until the end of the 21st century. 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 on the summers expressing relatively small number of large fires (Table 7). In spite of large inter-model variability, the number of large forest fires is expected to be in the late 21st century during a typical year close to that currently during those years with most 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 mostly suggested in recent studies (e.g. Teutschbein and Seibert, 2012). Quantile mapping has been previously successfully applied also for correcting relative humidity and wind speed simulations (Wilcke et al., 2013). Moreover, Yang et al. (2015) used 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 complex 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 the Finnish conditions (Vajda et al., 2014).

The developed regression models for estimation of the number of large forest fires and burned area have some uncertainties. Although the models performed well within the period 1996–2014, it is not certain that a similar relationship between fire weather and fire activity would still hold if the fire weather would turn much more severe. On the other hand, as most of large forest fires occur when moderate fire danger is prevailing, the change in the most extreme conditions has less relevance because those situations will in any case occur relatively rarely. The use of 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. On the other hand, this is also one source of uncertainty. Currently, most of large forest fires in Finland occur within a relative short period in May and early June as a result of human activities including often prescribed burnings and burning of trashes. It may have an impact on the fire activity whether these activities are in the future still conducted during the same time of year or whether they will be advanced 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 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 projected increase in fire danger during mid 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 of 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. The estimates given for burned area are highly uncertain, mostly because the occurrence

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only of a few conflagrations would increase the burned area by hundreds percent from the present levels. 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 escape to conflagrations. It is thus utmost important to suppress the fires as quickly as possible which may prove to be problematic if multiple fires on isolated locations are ignited within a short time. This is furthermore illustrated by the fact that even the largest forest fires during the recent decades were not associated with exceptionally severe fire weather. For instance, the Västmanland wildfire in Sweden in 2014 was escaped due to a delay in fire suppression because the fire fighters were at first send to a wrong location.

Considering the multi-model mean, the present projections for the number of large forest fires and burned area show clearly 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. However, the projected increase in the number of large forest fires is not that much larger than the projected increase in SSR. An additional explanation is that the RCP8.5 scenario is 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 under 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).

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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 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 showed curiously an abrupt doubling of the annual burned area in northern Europe around 2010 and no coherent change after that under the modest SRES A1B climate change 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, fire season is also expected to start earlier because of earlier snow melt (Räisänen and Eklund, 2012) and earlier commencement of the growing season (Ruosteenoja et al., 2011). In autumn, considerably lengthening of fire season is not probable because air humidity increases towards winter due to shortening day length.

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Previously, it had been shown that the meteorological forest-fire danger in Finland is on average higher in the south than in the north (Larjavaara et al., 2004; Kilpeläinen et al., 2010) and also that lightning ignites forest fires more frequently in southern Finland compared to northern Finland (Larjavaara et al., 2005). We showed that the fire activity also correlates strongly with population density which has a strong north–south gradient in Finland. However, the occurrence of large forest fires was not found to depend strongly on the population density, mainly because the average size of forest fires was found to decrease with increasing population density.

Intriguingly, the largest forest fires during the recent a few decades were not found to be associated with extremely severity of fire weather. Nevertheless, above-average DSRs were observed in each case and the frequencies for DSR values around the ignition dates varied approximately between 0.5–10 days yr^{-1}. This reflects the coincidental nature of the occurrence of wildland fires: a fire cannot occur without an ignition source regardless of a fire danger level. Although large fires become more probable with increasing fire weather severity, the probability of a large forest fire to occur in a single $0.1^{\circ} \times 0.2^{\circ}$ grid cell in a given day is only about 0.3 ‰ even with a DSR value of as high as 15 (Fig. 2). Consequently, a large majority of days with severe fire weather are non-fire days in Finland.

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 consisting mainly small-scale fires would be because during the open season for elk hunters and also people involved with various gathering activities fill the forests and light campfires. Consistently with their hypothesis, we showed that most of large fires in July are ignited by lightning strikes. Moreover, the annual course of lightning-ignited large forest fires follows closely the annual lightning activity with a peak in July (A. Mäkelä et al., 2014). We also showed that there are not many large-scale fires in September. Note also that the shorter study period of Tanskanen and

Venäläinen (2008) consisted several years with an exceptionally dry September. The first and most prominent peak in fire activity in late May was considered surprising by Tanskanen and Venäläinen (2008) because previously, May had been considered a marginal part of fire season. They assumed that the majority of fires originated from silvicultural slash burning of cured vegetation and trash 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 much more large fires before mid-June than later in summer, the seasonal vegetation development might not be the main reason for higher ignition probabilities in early season found in fire statistics.

The robustness of our results is somewhat limited because the results are based only on five different climate models. However, with the help of this subset of models, we were already able to demonstrate the large extent of the inter-model variability related to the fire-risk projections. Within a larger model set, this variability would be probably still larger. To exemplify this, Yang et al. (2015) estimated based on results of a single climate model that northern Sweden in close proximity to Finland would face in the future lower fire risk than today. It was mainly because in their simulation climate was projected to become more humid while our projections indicated either little change in relative humidity or drier future conditions. In general, the large uncertainty ranges related to the fire-risk projections reflect that uncertainties related to changes in temperature, precipitation, wind and humidity climates all add uncertainty to the estimation of forest-fire risk. 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, there exists large uncertainty in the sign of the change.

4.3 Conclusions

The impact of climate change on forest-fire risk in Finland with emphasis on large-scale fires was studied using the statistically downscaled and bias-corrected daily output of

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five CMIP5 models. The regression models for estimating the number of large forest fires and burned area were constructed based on the fire statistics during the years 1996–2014. A strong correlation between fire activity and fire weather indices existed over this period. Our results show that the number of large forest fires may double or even triple by the end of this century but the projections also show large inter-model variability. Hence, the present results highlight the large uncertainty in the rate of the projected increase in forest-fire risk.

Our results largely confirmed the previous presumptions of Tanskanen and Venäläinen (2008) about the ignition sources of fires at different times of year. Human-caused large fires are greatly overrepresented 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 months. 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 to occur in Finland. 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 favorable. Even a single conflagration could burn more forest area that has been typically burned within one decade in Finland during the last half a century. Our results suggest that the probability for such an event to occur will increase. The highest projections for burned area to become realized would virtually require some fires comparable to the Västmanland wildfire to take place during the present century.

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Table 1. Conflagrations in Finland beginning from 1959 that burned at least 200 ha of forest. The 2014 Västmanland wildfire in Sweden is included as well. In the last two columns, are mentioned the weather stations and their observation periods that were used in calculating the return periods for the fire weather components associated with the fires.

Fire site	Ignition date	Burned area (ha)	Weather station	Observation period
Hyrynsalmi (64.7° N, 28.5° E)	~ 15 May 1959	200	Kajaani	1959–2000
Honkajoki/Isojoki (62.1° N, 22.1° E)	19 Jul 1959	1600	Kankaanpää	1959–2010
Tuntsa (67.7° N, 29.6° E)	~ 30 Jun 1960	120 000 (total) 20 000 (in Finland)	Sodankylä	1960–2010
Rantsila (64.5° N, 25.7° E)	21 Jul 1969	650	Oulu	1960–2000
Tyrnävä/Muhos (64.8° N, 25.8° E)	9 Aug 1969	1300	Oulu	1960–2000
Kalajoki (64.3° N, 23.9° E)	24 Jun 1970	1600	Kruunupyy	1961–1994
Liminka (64.8° N, 25.4° E)	26 Jun 1970	500	Oulu	1960–2000
Tammela (60.8° N, 23.9° E)	9 Jun 1997	200	Jokioinen	1961–2010
Sala/Surahammar, Sweden (59.9° N, 16.1° E)	31 Jul 2014	15 000	Sala	1996–2014

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Table 2. 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 (lon × 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	US	$C48$ (2.5° × 2.0°), $L48$	Donner et al. (2011)
HadGEM2-ES	UK	1.25° × 1.875°, $L38$	Collins et al. (2011)
MIROC5	Japan	$T85$ (1.4° × 1.4°), $L40$	Watanabe et al. (2010)

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Table 3. 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
Apr	69.58	1.97	0.54
May	52.96	1.07	0.28
Jun	6.85	2.71	0.67
Jul	7.67	2.58	0.83
Aug	10.33	2.61	0.56
Sep	16.37	2.97	0.67
Oct	7.96	1.23	0.42

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Table 4. Statistics for the model validation. The Pearson product–moment correlation coefficient ($p < 0.1^{*}$, $p < 0.01^{**}$, $p < 0.001^{***}$), Spearman's rank correlation coefficient ($p < 0.1^{*}$, $p < 0.01^{**}$, $p < 0.001^{***}$), the mean bias error and the root mean square error between the annual observed and modelled number of large forest fires and burned area (ha) in Finland during 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

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Table 5. 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

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Table 6. Recurrence levels (in years) of fire weather indices associated with conflagrations listed in Table 1. Recurrence levels are defined based on the highest value of each fire weather index between one day before and one day after the estimated or known ignition date. The recurrence level for FWI corresponds to that of DSR. The long names for fire weather indices are fine fuel moisture code (FFMC), duff moisture code (DMC), drought code (DC), initial spread index (ISI), build up index (BUI) and fire weather index (FWI).

Fire site	Ignition date	FFMC	DMC	DC	ISI	BUI	FWI
Hyrynsalmi	~ 15 May 1959	0.2	< 0.1	< 0.1	0.3	< 0.1	0.1
Honkajoki/Isojoki	19 Jul 1959	0.2	5.2	0.7	0.2	5.2	1.7
Tuntsa	~ 30 Jun 1960	0.1	0.1	< 0.1	0.3	0.1	0.8
Rantsila	21 Jul 1969	0.1	1.3	0.1	0.1	1.2	0.6
Tyrnävä/Muhos	9 Aug 1969	0.3	3.7	1.3	0.1	3.7	1.9
Kalajoki	24 Jun 1970	0.3	1.2	< 0.1	0.3	0.6	1.5
Liminka	26 Jun 1970	0.2	0.7	< 0.1	0.1	0.3	0.4
Tammela	9 Jun 1997	1.0	0.3	< 0.1	0.2	0.1	0.4
Sala/Surahammar	31 Jul 2014	< 0.1	0.1	0.1	< 0.1	0.1	< 0.1

Table 7. 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)

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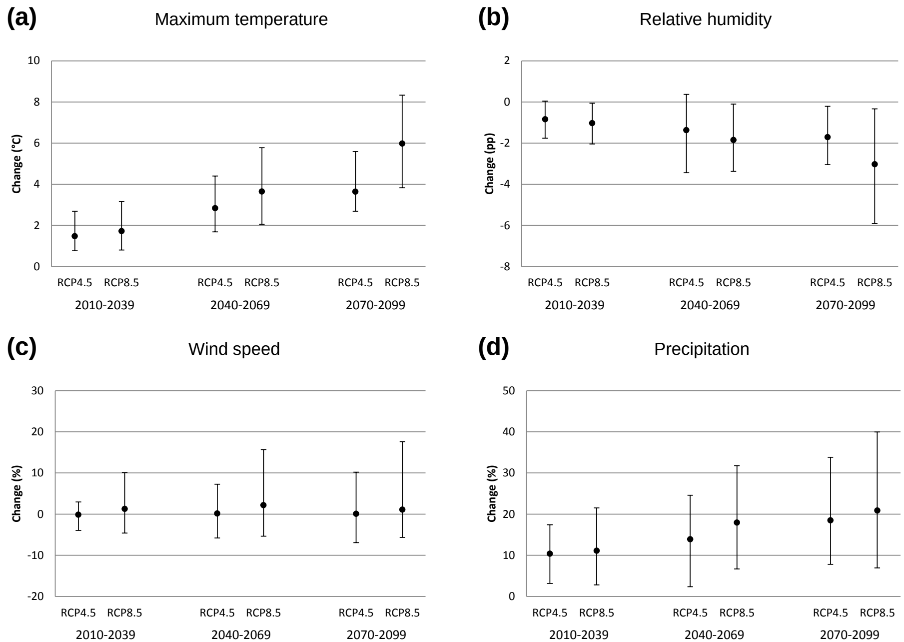

Figure 1. Projected changes in April–October mean daily maximum 2 m air temperature **(a)**, mean 2 m relative humidity **(b)**, mean 10 m wind speed **(c)**, and total precipitation **(d)** compared to the period 1980–2009 and averaged over the whole of Finland. Dots indicate the multi-model mean change and whiskers extend to the maximum and minimum projections.

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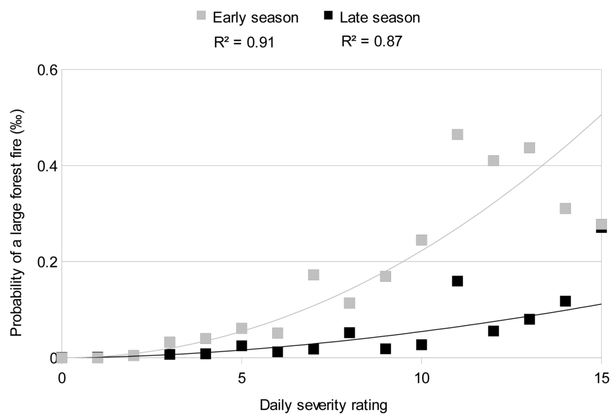

Figure 2. The relationship between daily severity rating (DSR) and occurrence of large forest fires in Finland during 1996–2014, separately for early (effective temperature sum below 250 °C days; grey squares) and late season (effective temperature sum above 250 °C days; black squares). The coefficients of determination of the power relations (R^2) are shown as well.

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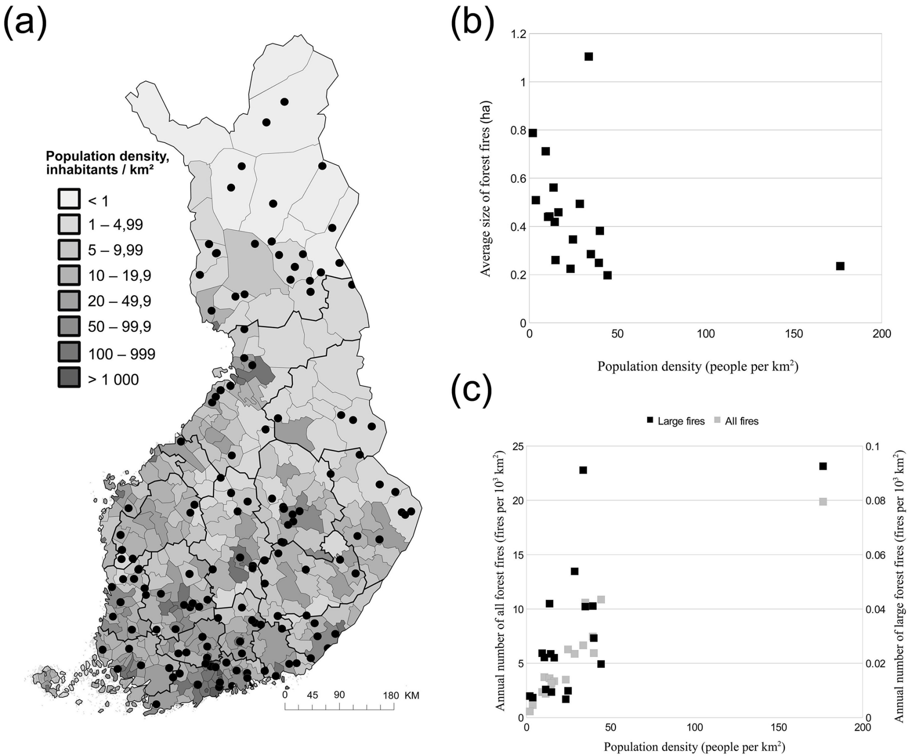

Figure 3. (a) Locations of large forest fires in Finland during 1996–2014 with population density by municipality. **(b)** Average size of forest fires in Finland by region during 1996–2014 as a function of population density. **(c)** Annual mean number of all forest fires (grey squares) and large forest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

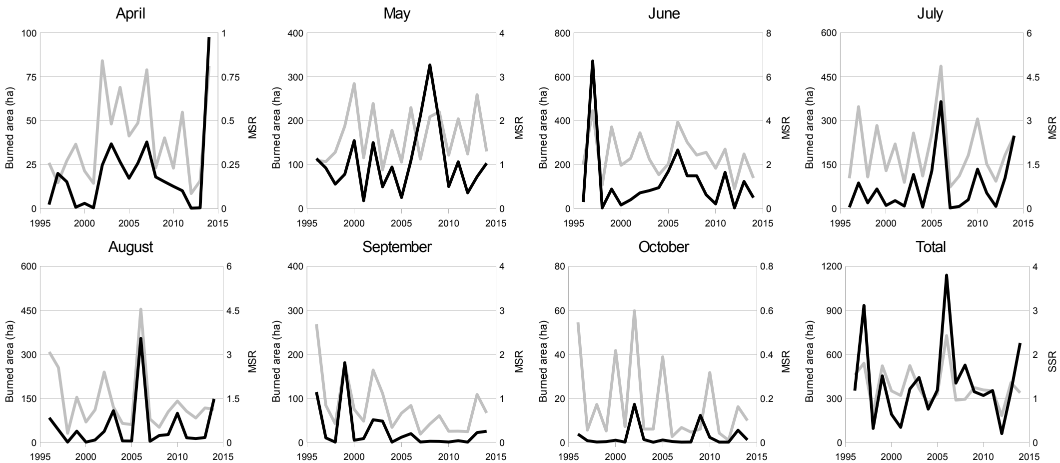

Figure 4. Burned forest area (black lines) in Finland by month and monthly severity rating (grey lines) averaged over whole of Finland during 1996–2014.

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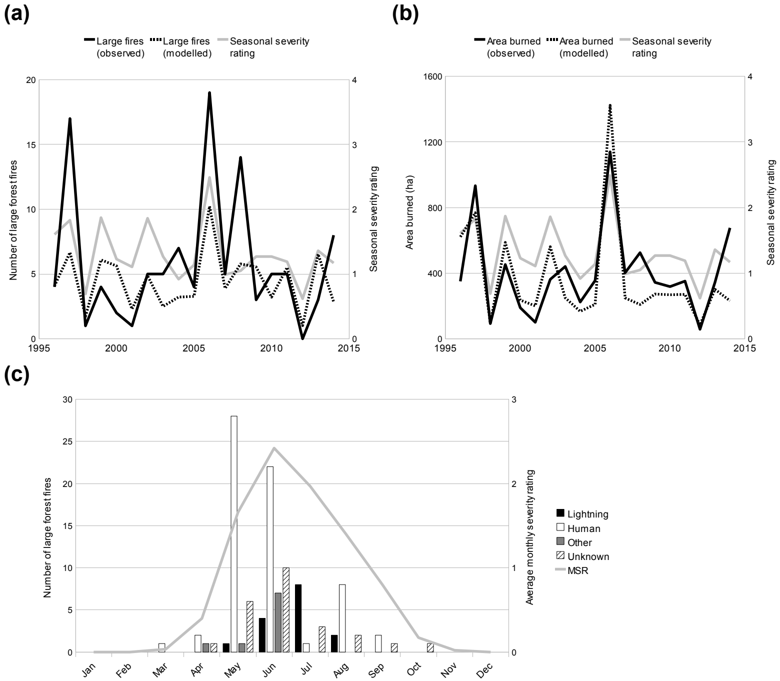

Figure 5. (a) Annual observed (solid black line) and modelled (dashed black line; based on Eq. 3) numbers of large forest fires in Finland during 1996–2014, as well as the annual April–October seasonal severity rating averaged over whole of Finland (grey line). **(b)** Annual observed (solid black line) 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 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).

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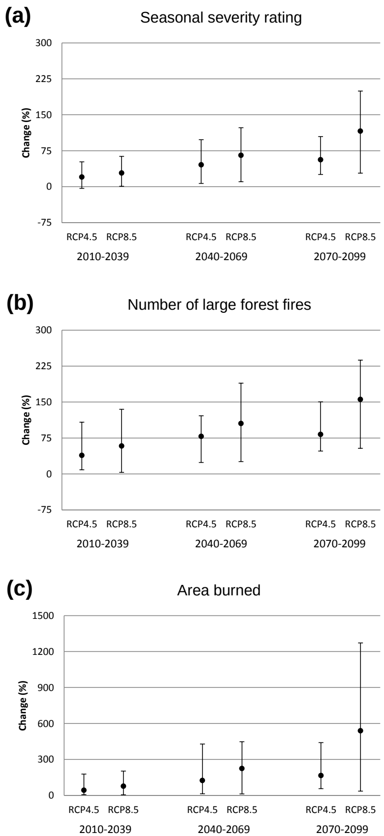

Figure 6. Projected changes in April–October seasonal severity rating averaged over whole of Finland **(a)**, in number of large forest fires in Finland **(b)**, and in area burned **(c)** compared to the period 1980–2009. Dots indicate the multi-model mean change and whiskers extend to the maximum and minimum projections.

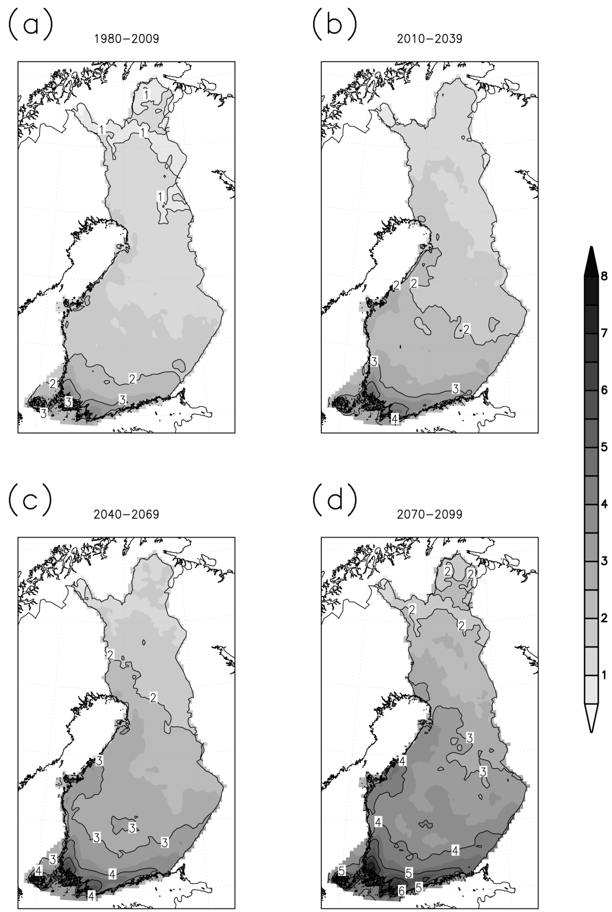

Figure 7. Projected multi-model mean for April–October seasonal severity rating (SSR) in 1980–2009 **(a)**, 2010–2039 **(b)**, 2040–2069 **(c)** and 2070–2099 **(d)** under the RCP8.5 scenario.