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Probabilistic projections of climatological forest fire danger in Finland

Hanna M. Mäkelä*, Ari Venäläinen, Kirsti Jylhä, Ilari Lehtonen, Hilppa Gregow

Finnish Meteorological Institute, Climate Service Centre, Erik Palménin aukio 1, PO Box 503, 00101 Helsinki, Finland

ABSTRACT: A multiple regression model was applied to estimate the future number of forest fire danger days (FDDs) in boreal climate conditions in Finland. The model used anomalies of June–August mean temperature and precipitation as predictors. Joint probability distribution functions (PDFs) created during the ENSEMBLES project for the SRES A1B scenario were employed to describe the future climate. The PDFs showed that the summertime mean temperature will, on average, rise in our study area by 1.5°C by 2010–2029 and by 4°C by 2080–2099. For precipitation, the PDFs showed a wide spread. Apart from western Finland, a majority of sample points suggested an increase in precipitation by the end of the century. Despite the general precipitation increase, average FDDs are likely to increase in the whole study area. Depending on the study region, the probability of FDD increase was 56 to 75% for 2010–2029 and 71 to 91% for 2080–2099. The largest probabilities of an increase were found in northern Finland and the smallest in eastern Finland. On average, FDDs were projected to increase by 1 d during the near future and by 7 to 10 d by the end of this century. The relative increase in FDDs was largest in northern Finland, by 12% in 2010–2029 and 55% in 2080–2099. The large uncertainty in future summertime precipitation is reflected in the estimation of future FDDs. Better estimates of spatial and temporal distribution of future precipitation would make the FDD assessment more robust.

KEY WORDS: Summertime average climate · Climate change · Forest fire danger · Fire danger model · Boreal environment

1. INTRODUCTION

The vast forest areas in the boreal vegetation zone have a considerable influence on the world's climate (Ruckstuhl et al. 2008, and references therein). For example, boreal forests contain >30% of all carbon present in the terrestrial biome (Kasischke 2000) and thus play a major role in the global carbon cycle. One of the main natural disturbances, in addition to, e.g. storms, insects, pathogens and floods, in these areas is fire (e.g. Kuuluvainen 2002, Hanewinkel et al. 2010). When burned, a forest stand will release a substantial amount of carbon into the atmosphere (Konovalov et al. 2011), and it will also cause a decrease in the carbon sink by reducing the photosynthetic capacity in that area (Conard & Ivanova 1997, Ruckstuhl et al. 2008). Forest fires also affect air quality and even human health through the emissions from burning biomass (Fowler 2003, Konovalov et al. 2011). The areas of influence can be wide: for example, smoke plumes originating from large wildfires in Russia in 2010 were observed at locations over 1000 km from the actual fires (Mielonen et al. 2012). From the socio-economical point of view, information about forest fire danger is highly relevant for the planning of future measures in e.g. forestry or rescue services. Knowledge of the probable magnitude of forest fire danger in the future enables the assessment of risk levels and the scaling of adaptation measures accordingly. In Europe, the most heavily forested country is Finland, with ~75% of its land area (23 million ha) cov-

*Corresponding author: hanna.makela@fmi.fi

ered by forests (Finnish Ministry of Agriculture and Forestry 2007).

Nowadays, the majority of the forest fires in boreal forests are ignited by humans instead of by natural causes, of which the most significant are lightning strikes (Larjavaara et al. 2005, Wallenius 2008). However, climate and prevailing weather play critical roles in preconditioning a forest stand as favourable to fire ignition and spread. Increasing temperatures and precipitation amounts have opposite influences on forest fire danger, the former increasing the danger and the latter lowering it. In Northern Europe, future climate projections are consistent in predicting increases in mean temperature for the boreal forest zone towards the end of the century. Warming will be most pronounced in winter, while summertime warming will be more modest (IPCC 2007). In Finland, the summertime mean temperature is projected to increase by 1 to 5°C by the end of the century compared to the period 1971 to 2000 (Jylhä et al. 2009). Future projections for precipitation amounts in this area show an inter-model agreement for an increasing tendency in wintertime. Summertime precipitation projections are more uncertain, with increasing amounts in the future more likely than diminishing totals (IPCC 2007, Jylhä et al. 2009, Ylhäisi et al. 2010).

Climate models provide an indispensable means of estimating future climate conditions. However, many factors still affect the uncertainty of future climate predictions, e.g. the inability of the models to describe small-scale processes (such as clouds), uncertainties in the radiative forcing components (e.g. aerosol effects), and our limited understanding not only of the interactions among the various different components of the physical climate system but also of the socio-economic and technological variables in general (e.g. IPCC 2007, Webster et al. 2002, Räisänen 2007). Oreskes et al. (2010) also listed several reasons why the information about the future climate as provided by climate models is not completely applicable for risk management and adaptation, including problems in the simulation of small-scale processes and the lack of a realistic evaluation of extremes. One way to assess uncertainties in climate models is to use probability distribution functions (PDFs) (e.g. Pittock et al. 2001, Räisänen & Ruokolainen 2006, Tapiador et al. 2009, Fronzek et al. 2010, Harris et al. 2010).

Forest fires occur in Finland typically from April to September, with the peak season from late May to August (Saari 1923, Laitakari 1960). During the past 3 decades, the average number of forest fires has been ~1000 fires annually, with an average burnt area of 0.5 ha per fire (Finnish Forest Research Institute 2012). In addition to true forest fires, there also exist a great number of other wildfires, including e.g. grasslands and bushes, but those are not considered in the above-mentioned figures. In Finland, an efficient fire prevention and suppression system helps to keep forest fires small (Finnish Ministry of Agriculture and Forestry 2007). A relatively dense forest road network intersecting the extensive forest areas both isolates the burning areas and enables swift access to the fire sites. However, large fires with burnt areas of thousands of hectares are possible. Probably the most well-known one is that in Tuntsa in eastern Lapland in 1960, with a burnt area of ~20 000 ha (Vajda 2007). In addition, conflagrations with burnt areas of millions of hectares occur yearly in neighbouring Russia (Vivchar 2011).

During the 20th century, forest fire danger in Finland has varied from year to year. There has been no significant increasing or decreasing tendency in the climate-driven forest fire danger (Mäkelä et al. 2012), even though summertime temperatures have increased (Tuomenvirta 2004, Tietäväinen et al. 2010). There have not, however, been any significant changes in summertime precipitation amounts either (Ylhäisi et al. 2010). For the future forest fire danger analysis, Lehtonen et al. (2014a) emphasized the difficulty of distinguishing the climate change signal from the large natural inter-annual variability, especially in the most recent decades. They estimated the number of days with elevated forest fire danger in typical northern boreal forest stands to increase by 10 to 40% by the end of this century, depending on the emission scenario. In their study, the Canadian fire weather index was used. According to Kilpeläinen et al. (2010), a rise in evaporation demand will increase the forest fire potential in Finland, especially in the southern parts, by the end of this century. According to them, the expected increase in the annual frequency of forest fires over the whole country is ~20% compared to the present day if the pessimistic Special Report on Emission Scenarios (SRES) A2 emission scenario (Nakičenovič et al. 2000) materializes. Increases in future fire danger levels, larger burnt areas and an earlier start to fire season are also projected for other parts of the boreal zone (Stocks et al. 1998) and in parts of Southern and Central Europe (Camia et al. 2008).

The objective of this work is to study the number of days with a high forest fire danger in Finland under the future summertime (June–August) climate and to estimate the uncertainties related to the assessment.

A multiple linear regression model is used to combine the fire danger information with the seasonal mean temperature and the precipitation sum (Mäkelä et al. 2012). Use of probabilistic climate projections allows an estimation of the probability of the future forest fire danger's magnitude. The joint PDFs for seasonal and annual temperature and precipitation change were made available for various regions in Europe as a part of the ENSEMBLES project (van der Linden & Mitchell 2009), and these are utilized in this study. With the phrase 'forest fire danger', we refer to a forest stand's suspectibility to fire in terms of climatic conditions only.

2. DATA AND METHODS

This study combined observed monthly mean temperature and precipitation sum data and daily fire danger data of the current climate with probabilistic future projections of seasonal-mean changes in temperature and precipitation to produce seasonal information about the future fire danger. A simple fire danger day (FDD) model using only seasonal climate values was used due to the limitations of the future probabilistic meteorological input data. The study area comprised 4 HadCM3 grid boxes (Gordon et al. 2000) located in Finland (Fig. 1) and denoted by WF (Western Finland), EF (Eastern Finland), EB (East Bothnia) and FL (Finnish Lapland).

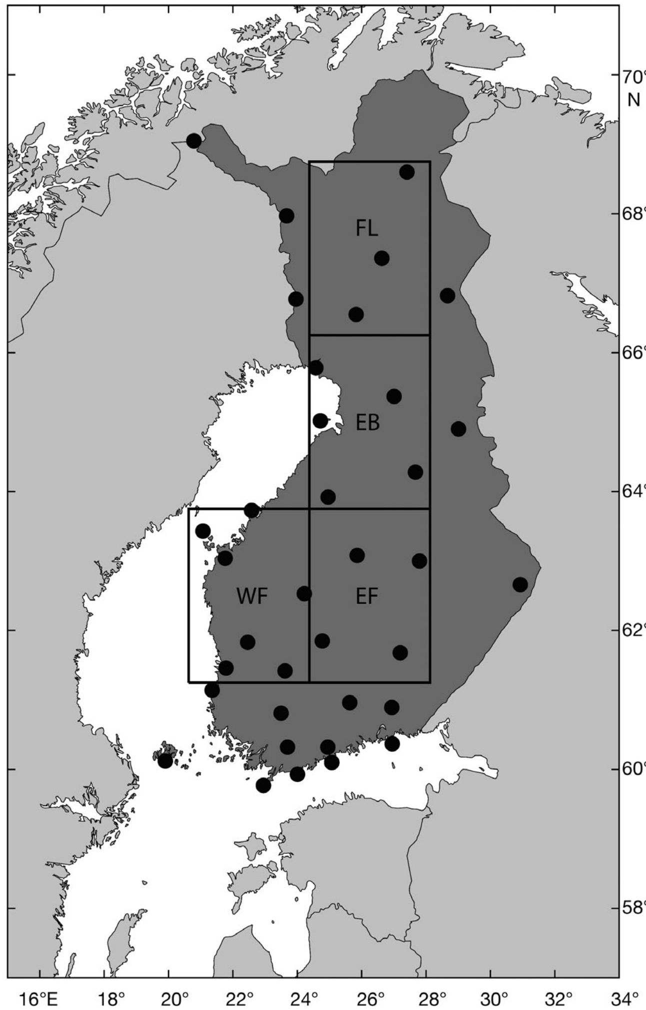

Fig. 1. Study area showing the HadCM3 grid points (WF: Western Finland, EF: Eastern Finland, EB: East Bothnia, FL: Finnish Lapland) and the locations of the weather stations with FFI data. Dark grey: Finland

2.1. Finnish forest fire danger rating

The seasonal forest fire danger was defined as the number of days with an elevated forest fire danger as given below during June to August. The assessment of daily fire danger was based on a numerical forest fire danger-rating method, the Finnish Forest Fire Index (FFI), which has been developed especially for the boreal forest environment (Heikinheimo et al. 1998, Venäläinen & Heikinheimo 2003, Vajda et al. 2013). The method is routinely used in Finland. The method is based on the volumetric moisture content of a 6 cm thick soil surface layer, which is calculated based on precipitation and potential evaporation data. Actual evaporation from the surface is calculated using the Penman-Monteith equation (Monteith 1981). The volumetric moisture is scaled to forest fire index values between 1 and 6, with 1 indicating the lowest and 6 the highest possible fire danger in terms of fuel moisture. A forest fire warning is declared with index values of ≥4. In this work, a day with an FFI value of at least 4 is denoted an FDD. Vajda et al. (2013) recently compared FFI with one of the most widely-used fire indices, Van Wagner's (1987) Fire Weather Index (FWI), and evaluated their performance as forest fire danger predictors. Even though the 2 fire indices generally agreed on predicting the fire danger in Finland, less than half of fire days were being successfully predicted. The performance was best for fires in southern Finland and poorest in the north. Regional differences were mainly due to sparse population density in northern Finland, which means that fewer fires are ignited and observed there compared to the southern parts of the country. Vajda et al. (2013) stated that it is important to take into account the fact that the number of fires detected does not correlate directly with the fire danger index data. For example, the efficient warning system in Finland most likely changes human fire-handling behaviour during the high fire danger periods, resulting in a reduced number of fires than the potential number without fire danger warning.

New FFI values are calculated every 3 h. It is this requirement for meteorological data at a high temporal resolution that limits the use of FFI (or other numerical fire indices, e.g. FWI) for the extensive assessment of past and future fire danger. However, even with coarser input data, such as seasonal climatic values (Mäkelä et al. 2012, Duffy et al. 2005, Achard et al. 2008), or information about large-scale climatic patterns (Macias Fauria & Johnson 2008), one can tolerably assess the season's fire danger in general.

Mäkelä et al. (2012) used daily FFI data from 36 weather stations located around Finland (Fig. 1) to produce 10 km resolution gridded data of the summertime (June–August) FDDs. Because of the availability of the FFI data, the interpolated FDD fields covered the years 1961 to 1997. We used these fields to calculate the FDDs for the 4 study regions (Fig. 1). Regional values of FDDs were created by taking an arithmetic mean over all the grid points in a region. The observation stations with FFI data were located throughout Finland, the coverage density being higher in the south and west than in the north and east (Fig. 1), following the distribution of meteorological observation stations in Finland. The HadCM3 grid boxes over Finland were also located more in western than in eastern Finland (Fig. 1).

Table 1. Linear multiregression functions, adjusted coefficient of determination (adjusted R^2) and standard error of the residuals for each of the study regions. ΔX_T and ΔX_P refer to the deviation of the June–August mean temperature (°C) and precipitation sum (%) from the long-term (1961 to 1990) mean, respectively

Region	Regression function ($a\Delta X_T + b\Delta X_P + c$)	Adjusted R^2	Residual standard error
Western Finland	$2.21\Delta X_T - 0.38\Delta X_P + 31.59$	0.661	7.533
Eastern Finland	$3.53\Delta X_T - 0.34\Delta X_P + 22.44$	0.627	6.539
East Bothnia	$2.52\Delta X_T - 0.39\Delta X_P + 23.76$	0.659	7.688
Finnish Lapland	$2.55\Delta X_T - 0.25\Delta X_P + 17.76$	0.534	7.390

2.2. Regression model for fire danger

To be able to develop probabilistic scenarios for FDDs, we followed the approach of Mäkelä et al. (2012) to construct a multiple linear regression model to approximate the dependence of the fire danger on the average summertime climate. According to this simple model, higher temperatures (T) and lower precipitation (P) amounts lead to more days with forest fire danger, and vice versa, as follows:

$$\mathrm{FDDs} = a\Delta \mathrm{T} + b\Delta \mathrm{P} + c \qquad (1)$$

where ΔT and ΔP denote the anomalies of June–August mean temperature (unit: °C) and precipitation sum (unit: %), respectively, from the corresponding long-term means (1961 to 1990). To determine the regression coefficients *a*, *b* and *c*, we ran a linear model fitting function over the time period of 1961 to 1997. The regional temperature and precipitation anomalies were derived from gridded monthly mean temperature and precipitation data with a 10 km resolution (Tietäväinen et al. 2010, Ylhäisi et al. 2010) using the kriging spatial interpolation method (e.g. Ripley 1981, Henttonen 1991, Aalto et al. 2013).

The mean temperature and precipitation sum of a fire season explained ~65% of the season's fire danger in Western and Eastern Finland and East Bothnia. In Finnish Lapland, the coefficient of determination was 0.53 (Table 1). The adjusted coefficient of determination (adjusted R^2) was used to avoid the misleading improvement of the regression coefficient due to multiple independent variables. Similar features of the determination coefficient for different Finnish regions were found by Mäkelä et al. (2012). According to their study, the June–August mean temperature and precipitation sum managed at its best to explain >70% of the season's fire danger in the southernmost and westernmost regions in Finland. All the coefficients in the regression functions (Table 1) were statistically significant ($p < 0.05$); thus, there are significant relationships between all the variables in the regression analyses. The validity of regression analysis was confirmed through underlying assumptions about linearity of the dependent and independent variables, normality and independence of the errors, and homoscedasticity. The standard error of the residuals varied around 7 d in all regions, the equivalent of 23% (WF) to 41% (FL) of the average number of FDDs. The FDD models tended to underestimate the extremes in the number of FDDs for all the regions, with the minimum values being too high and the maximum values too low (Fig. 2). The range of the modelled number of FDDs thus became narrowed. It was also possible for the FDD model to produce negative values: these were reset to zero. Based on the regres-

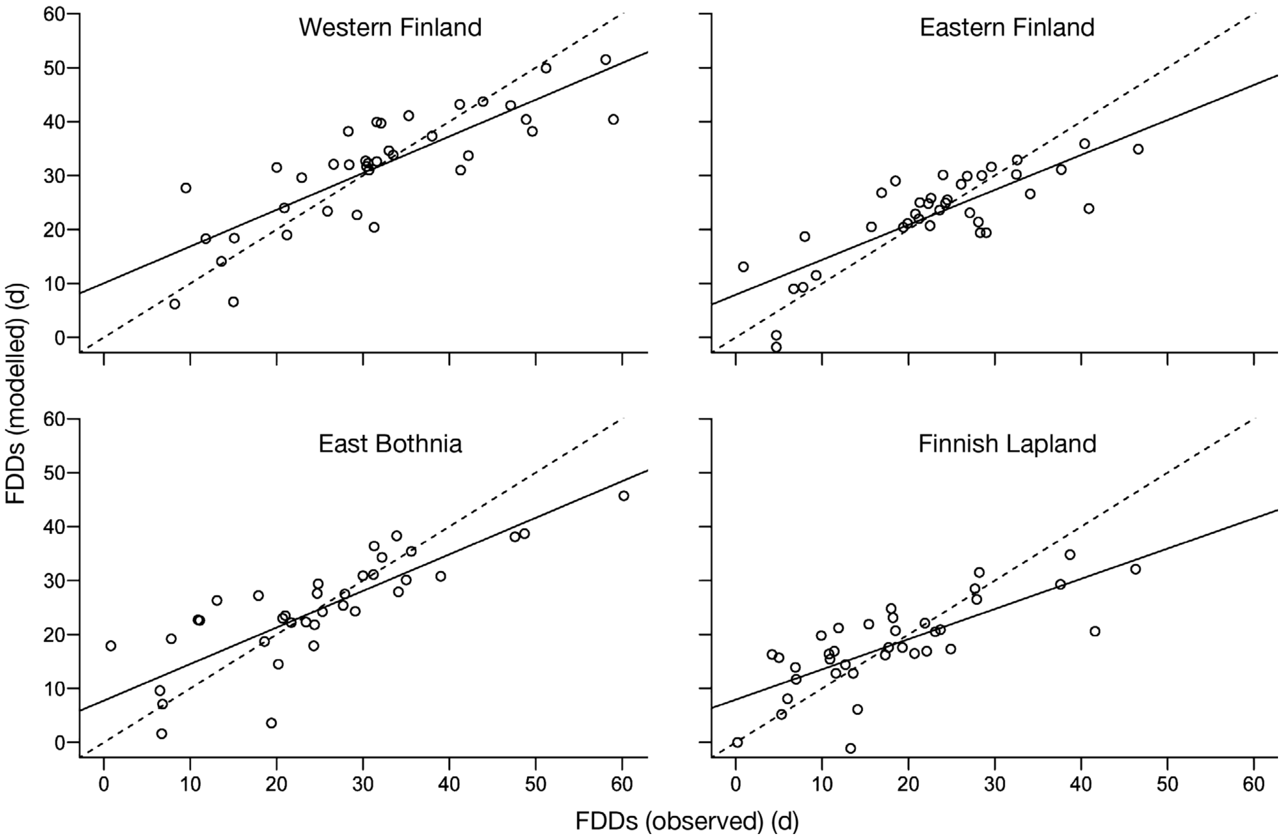

Fig. 2. Scatter plots of the observed and modelled number of fire danger days (FDDs) in the study regions in 1961 to 1997. The solid line shows the best least-squares fit for the data, whereas along the dashed line, the modelled FDD value equals the observed one

sion models (Table 1), response surface plots were constructed. The joint impact of temperature and precipitation anomalies on the number of FDDs was examined through them (see Figs. 3 & 4). For example, a 1° increase in June–August mean temperature resulted in 2 (WF) to 4 (EF) more FDDs. A 1° temperature increase was compensated by a 5 (WF) to 10% (EF and FL) increase in precipitation, corresponding to a precipitation amount of 11 (WF) or 22 mm (EF).

2.3. Development of future climate scenarios

To be able to assess the uncertainties related to the future scenarios of FDDs, we chose to use probabilistic climate projections for ΔT and ΔP. Joint probability distribution functions (PDFs) of future seasonal-mean changes in surface air temperature and precipitation in Europe (Harris et al. 2010) became available through the ENSEMBLES project (Hewitt 2004, van der Linden & Mitchell 2009). The future climate PDFs represent changes in 20 yr of average climate for decadal steps starting from the period 2010 to 2019 and finishing at 2080 to 2099 (Harris et al. 2010).

The PDFs are based on an equilibrium-perturbed physics ensemble of 280 simulations with the Hadley Centre atmosphere model coupled with the simple 'slab ocean' (HadSM3) (Williams et al. 2001) and a doubling of CO_2. The ensemble sample size was increased further by Harris et al. (2010) with the aid of an emulator (Rougier et al. 2009). Furthermore, Harris et al. (2010) supplemented these simulations with smaller transient ensembles (4 ensembles each with 16 members) using a fully coupled HadCM3 version with a dynamic ocean model and sea-ice, aerosol and land-carbon components included (Gordon et al. 2000). The residual error in HadSM3 simulations compared to both the observed past climate and unobserved future climate was represented by the structural differences between model projections in the CMIP3 archive (Meehl et al. 2007). According to Harris et al. (2010), the structural differences provide reasonable *a priori* estimates of possible structural errors between HadSM3 and the real world. The probabilistic predictions were made emphasiz-

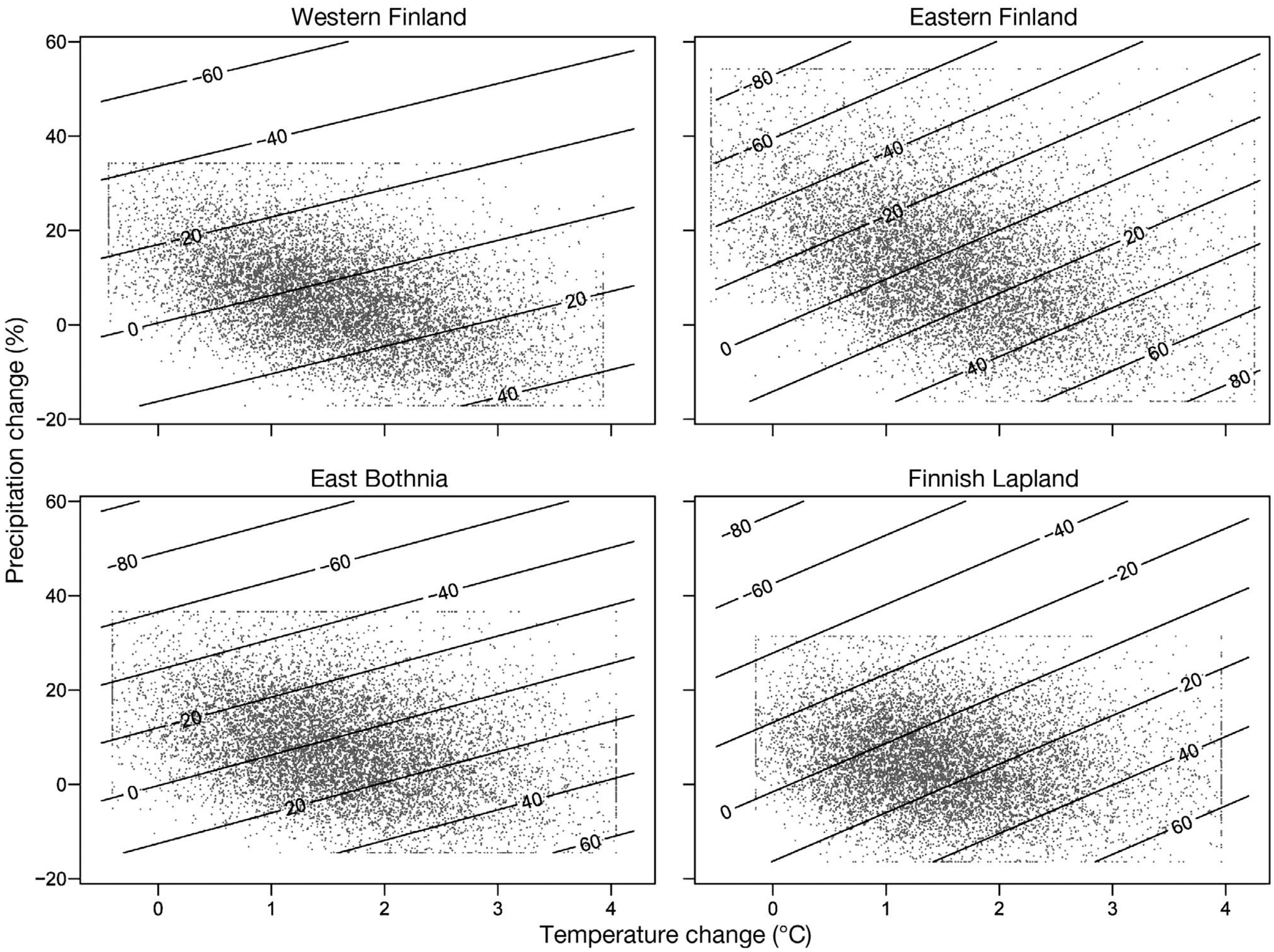

Fig. 3. Response surface plots showing the modelled change (%, solid lines) in the number of fire danger days as a function of June–August mean temperature (°C) and precipitation sum (%) anomalies from the 1961–1990 mean. The response surfaces are based on the regression functions fitted for the time period 1961 to 1997 (Table 1). The scattered points show the Winsorised 10 000 sample points from the joint PDFs of surface temperature change (°C) and percentage precipitation change for the future period 2010 to 2029 (Harris et al. 2010)

ing the subjective interpretation of probability, i.e. following a method based on a Bayesian approach by Rougier (2007). Murphy et al. (2009) applied the same method to provide climate predictions for the United Kingdom (UKCP09).

The PDFs are specific to the SRES A1B emission scenario (Nakičenovič et al. 2000) and have a baseline period of 1961 to 1990. The future climate distributions represent a quantification of the uncertainty related to major known physical, chemical and biological feedbacks (Harris et al. 2010). The projections were made at HadCM3 (Gordon et al. 2000) global climate model spatial scales of ~300 km resolution without any regional downscaling. The projections are available for >100 regions in Europe following the HadCM3 grid of 2.5° latitude by 3.75° longitude. We collected future climate projections for the grid points falling within the borders of Finland (Fig. 1) for 2 time slices: 2010 to 2029 for the present and near-future climate, and 2080 to 2099 for the climate at the end of this century.

The future climate data consisted of 10 000 sample values from the joint PDF for future temperature and precipitation change for each of the HadCM3 grid cells. Following the recommendation of Harris et al. (2010), we mostly used the 10th and 90th percentiles of the sample as a measure of the spread of the PDFs. According to Harris et al. (2010), less confidence can be placed in the extreme percentiles compared with the moderate ones because the extremes are more sensitive to the statistical assumptions in the methodology. In addition, Harris et al. (2010) reset sample points situating below the 1st and above the 99th percentile to the 1st and 99th percentile, respectively ('Winsorising'), to eliminate non-robust sample points. This can be seen as an accumulation of the

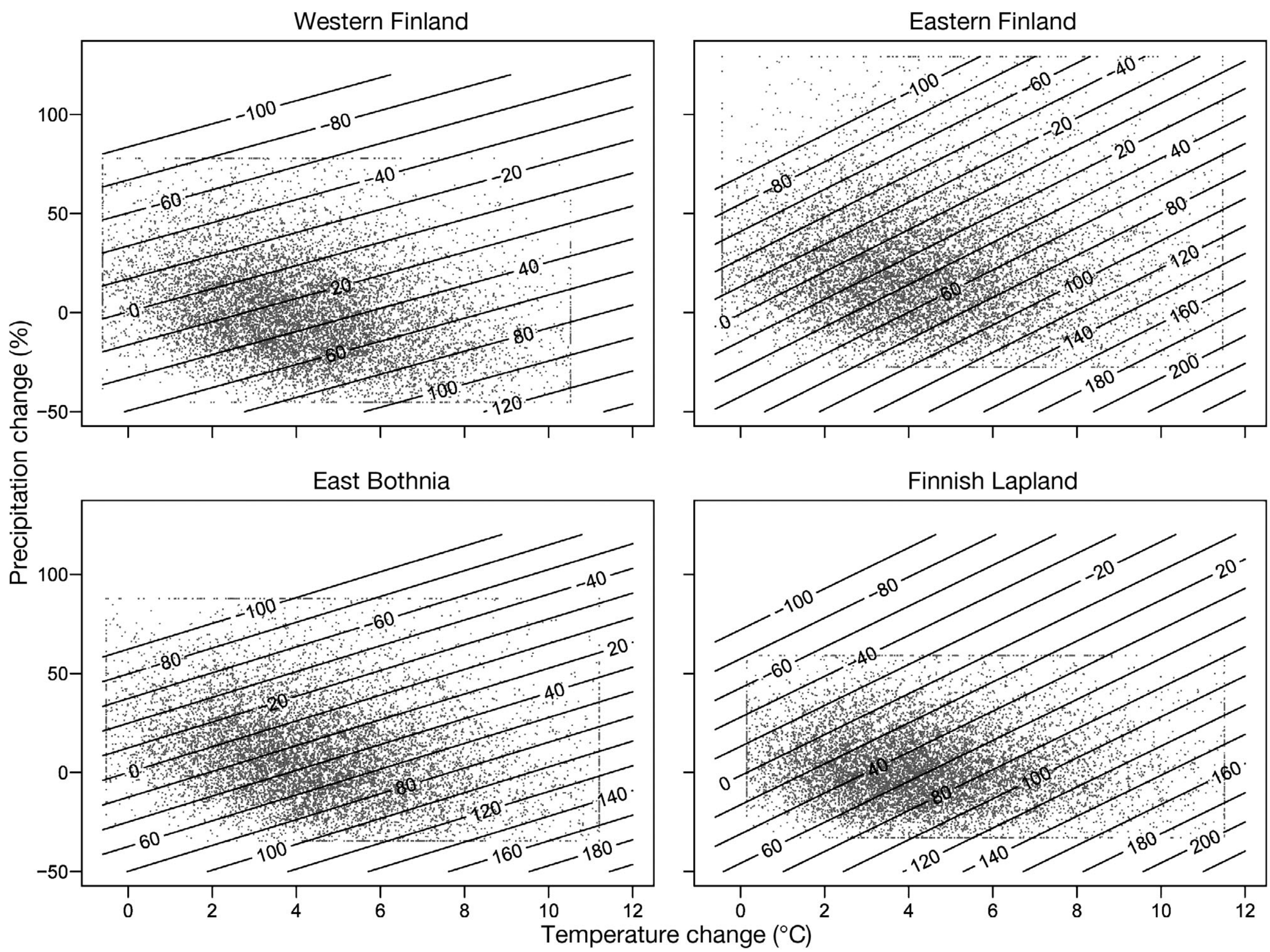

Fig. 4. As Fig. 3, but the scatter plots are for the period 2080 to 2099. Note the different axis scales compared to Fig. 3

sampled data points in the distributions' tails (see e.g. Figs. 3 & 4).

Finally, the future PDFs of FDDs were computed by running the FDD model with the projections of the future seasonal-mean temperature and precipitation change for the desired time periods 2010 to 2029 and 2080 to 2099.

3. RESULTS

3.1. Current and future temperature and precipitation climate

Due to Finland's large area and its location between the continental and maritime climatic zones, local climatic conditions vary from one study region to another (Table 2). During the reference period 1961 to 1990, the summertime (June–August) mean temperature ranged from almost 12°C in Finnish Lapland to over 14°C in Western and Eastern Finland. Average summertime precipitation was lowest (189 mm) in Western Finland and Finnish Lapland and highest (215 mm) in Eastern Finland.

For each of the 4 study regions, the future climate projections predicted, with a high level of consistency higher summertime temperatures compared to the reference period 1961 to 1990 (Figs. 3 & 4). In 2010 to 2029, the temperature change was positive in 95.7% (EF) to 98.5% (FL) of the sample points, whereas by the end of this century, 97.5% (WF) to 100% (FL) of the sample points were predicted to undergo increasing mean temperature. The ranges give the variation between the study areas. The average increase in June–August mean temperature was ~1.5°C by 2010 to 2029 and ~4.2°C by 2080 to 2099. Approximately 80% of the temperature projections fall between +0.4°C and +2.8°C in 2010 to 2029 and between +1.6°C and +7.5°C in 2080 to 2099 (Table 3).

Although a few decreasing projections did occur in almost all areas for temperature, the decreasing projections were more marked for precipitation

Table 2. Basic information about the study regions: the number of weather stations with Finnish Forest Fire Index (FFI) data and the summertime (June to August) mean temperature, precipitation sum and the number of fire danger days from 1961 to 1990. Parentheses: ranges

Region	No. of weather stns. with FFI data	Mean temperature (°C)	Precipitation sum (mm)	No. of fire danger days (d)
Western Finland	7	14.3 (12.1–16.4)	189 (99–320)	32 (8–59)
Eastern Finland	4	14.5 (12.2–16.9)	215 (149–355)	23 (1–47)
East Bothnia	5	13.5 (11.3–15.9)	197 (93–331)	24 (1–60)
Finnish Lapland	3	11.8 (9.7–14.2)	189 (106–301)	18 (0–46)

(Figs. 3 & 4). For the earlier time period, 2010 to 2029, 68.8% (FL) to 83.7% (EF) of the sample points predicted an increase in the season's precipitation sum. For the latter time period, 2080 to 2099, 47.7% (WF) to 79.9% (EF) of the sample points gave a positive change for the precipitation sum. Thus, by the end of the century, the summertime mean precipitation was even expected to decrease in Western Finland. The precipitation increase ranged from 5% (FL) to 13% (EF) in 2010 to 2029 and from −2% (WF) to 20% (EF) in 2080 to 2099. The range (10th to 90th percentile) was large; e.g. in Eastern Finland, where the range was the largest, the percentage change in the seasonal precipitation sum relative to 1961 to 1990 varied from −3.3% to +32.1% in 2010 to 2029 and from −8.4% to +62.8% in 2080 to 2099 (Table 3).

3.2. Current and future number of FDDs

As shown by Table 2, during the reference period 1961 to 1990, the lowest number of FDDs according to the daily FFI data was found in Finnish Lapland (on average 18 d) and the highest in Western Finland (32 d). Similar regional features for the average number of FDDs were found by Mäkelä et al. (2012) for 1980 to 2010.

The average number of FDDs was likely to increase in all the regions and for both future time periods (Figs. 5 & 6). The probability of the increase was larger in the latter time period. Around 56 to 75% of the PDFs' sample points predicted an increase in FDDs for 2010 to 2029, and around 71 to 91% for 2080 to 2099. The largest probabilities for an increase were found in Finnish Lapland, and the smallest in Eastern Finland. In the 3 southernmost regions, Western and Eastern Finland and East Bothnia, the increase in the average number of FDDs by 2010 to 2029 was most likely to be around 4%, and in Finnish Lapland, this increase was around 12% (Table 3). By 2080 to 2099, FDDs increased by approximately one-third in Western and Eastern Finland and East Bothnia and by ~50% in Finnish Lapland. The relative increase was clearly largest in Finnish Lapland, where the FDDs were initially lower (an equal FDD increase in days corresponds to a larger relative change). This pattern means ~1 FDD more in 2010 to 2029 and 7 to 10 d more in 2080 to 2099 (Table 3). Due to the considerable uncertainty in the future precipitation estimates, there are also large variations in the FDD estimates. For example, in Eastern Finland by the end of this century, the FDD estimates vary from −42% (−10 d) to +103% (+23 d).

Table 3. Percentiles of the predicted changes in June–August mean temperature, precipitation sum and number of fire danger days (FDDs) in each of the study regions according to future climate projections for 2010 to 2029 and 2080 to 2099. The changes are presented relative to 1961 to 1990. In the last column, the corresponding number of FDDs in June to August is shown. (WF: Western Finland, EF: Eastern Finland, EB: East Bothnia, FL: Finnish Lapland). Data are 50th (10th–90th) percentiles

	ΔMean temperature (°C)	ΔPrecipitation sum (%)	ΔNo. of FDDs (d)	ΔNo. of FDDs (%)	No. of FDDs (d)
2010 to 2029					
WF	1.5 (0.4 to 2.7)	5.6 (−7.3 to 19.6)	1 (−5 to 8)	4.4 (−17.0 to 25.1)	33 (26 to 39)
EF	1.5 (0.4 to 2.9)	12.5 (−3.3 to 32.1)	1 (−8 to 9)	4.2 (−35.2 to 41.2)	24 (15 to 32)
EB	1.5 (0.5 to 2.8)	7.8 (−4.6 to 21.6)	1 (−6 to 7)	3.5 (−25.2 to 30.5)	25 (18 to 31)
FL	1.4 (0.5 to 2.6)	4.5 (−6.9 to 17.8)	2 (−2 to 7)	11.9 (−11.7 to 36.4)	20 (16 to 25)
2080 to 2099					
WF	4.0 (1.4 to 7.2)	to 1.5 (−28.4 to 34.3)	9 (−7 to 23)	29.5 (−20.5 to 74.4)	41 (25 to 55)
EF	4.2 (1.4 to 7.6)	19.9 (−8.4 to 62.8)	7 (−10 to 23)	32.1 (−42.4 to 103.2)	30 (13 to 46)
EB	4.3 (1.6 to 7.6)	7.6 (−18.9 to 43.1)	8 (−9 to 23)	31.5 (−37.3 to 94.0)	31 (15 to 46)
FL	4.2 (1.8 to 7.6)	1.1 (−19.4 to 29.7)	10 (1 to 20)	55.2 (3.1 to 109.6)	28 (19 to 38)

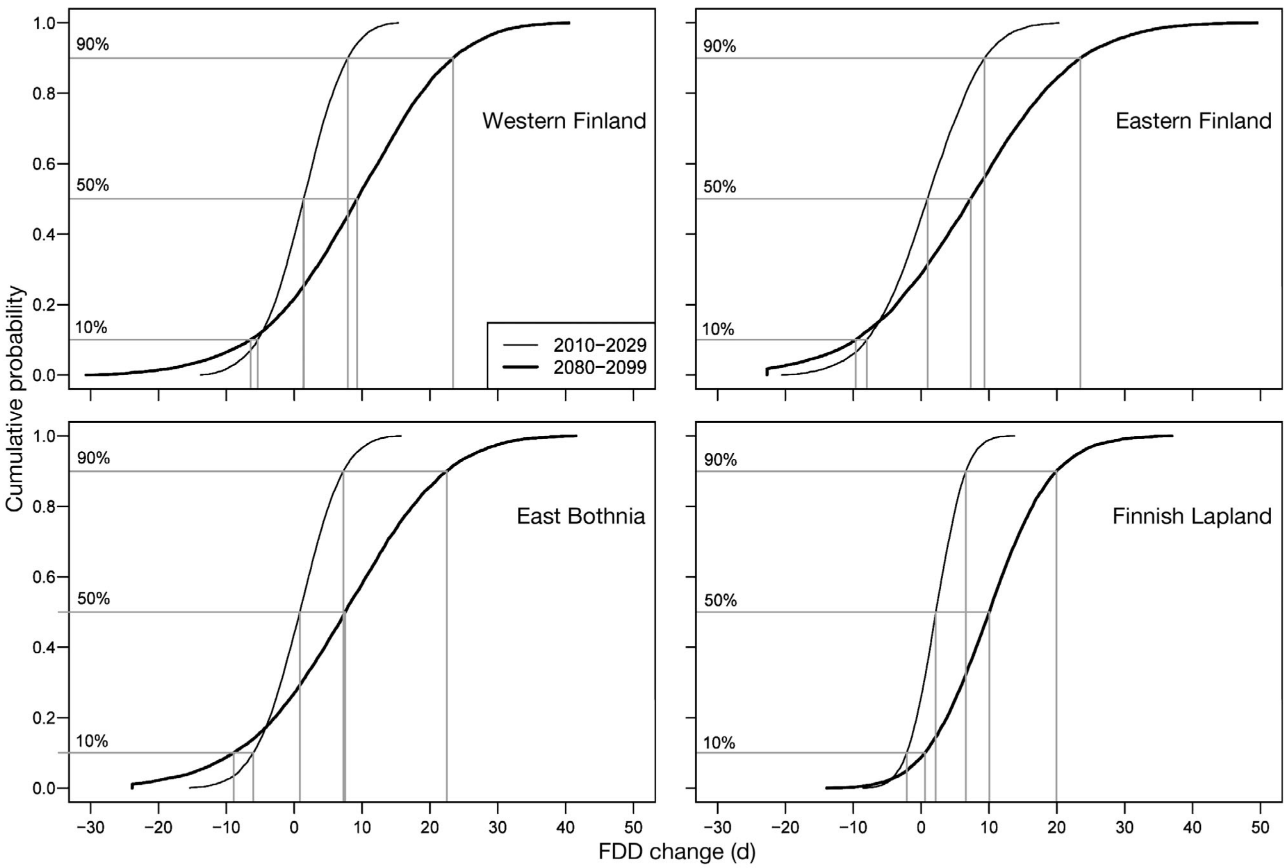

Fig. 5. Cumulative probabilities of the change in the June–August number of fire danger days (FDDs) in each of the study regions. The 10th, 50th and 90th percentiles are shown with lines. The thin and thick curves denote the time periods 2010 to 2029 and 2080 to 2099, respectively

A temperature increase during this century is very likely in the whole study region according to the probability temperature projections (Table 3). Rising temperatures lead to more FDDs.

Because the future temperature estimates are so consistent, the sign and magnitude of future precipitation change is the main factor determining whether the number of forest FDDs increases or decreases in the future. The mean estimates of summertime precipitation change during this century vary considerably between the different study regions. For example, by the end of the 21st century, the June–August rain amount was likely to decrease by 1.5 % in Western Finland and increase by 20 % in Eastern Finland. Despite the large difference in the average precipitation projections, the average increase in FDDs in both areas was ~30 %. This result could be explained by the fact that FDDs were initially lower in Eastern Finland and that, relative to precipitation, temperature has a greater influence on FDDs there than in Western Finland (Table 1).

4. DISCUSSION AND CONCLUDING REMARKS

This work concentrated only on the forest fire 'high season', i.e. June to August. However, due to climate warming, the end of the snow season in the boreal environment will take place earlier in the future than today (Ruosteenoja et al. 2011, Räisänen & Eklund 2012), also promoting an earlier start to the fire season. Forest fire activity starts soon after snowmelt, when organic debris from the previous growing season is exposed and dried. Tanskanen & Venäläinen (2008) found indications of the fire activity already shifting towards the spring, and they related these shifts to the increased spring temperatures reported by Tuomenvirta (2004) and later also by Tietäväinen et al. (2010). Also, Westerling et al. (2006) associated the increased wildfire activity to increases in spring and summer temperatures and the earlier springtime snowmelt (in the Northern Rockies in the western USA). The advancing of the active fire season might lead to a notable increase in the total burnt area in

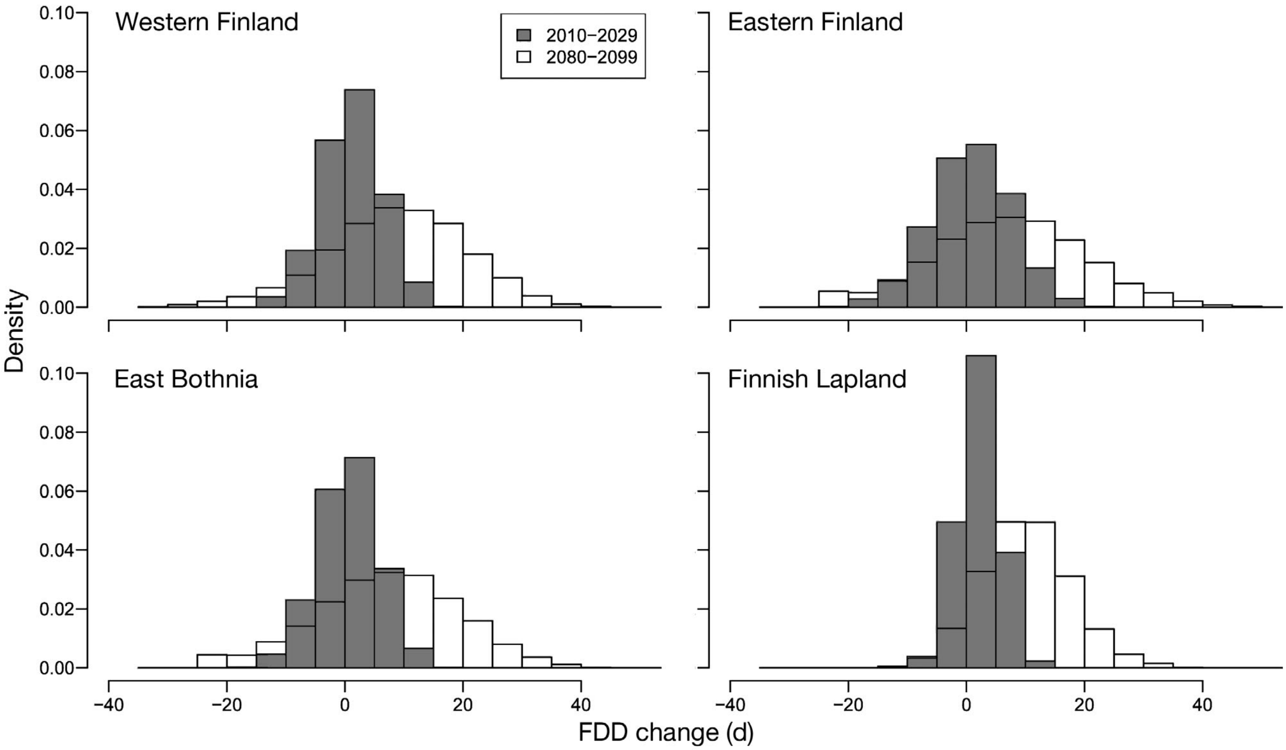

Fig. 6. Probability density of change in the number of fire danger days (FDDs [d]) by 2010–2029 (grey columns) and by 2080–2099 (unfilled columns) relative to the 1961–1990 baseline period

Finland, as, during past decades, the fires resulting in the largest burnt areas have occurred specifically in the early fire season (Tanskanen & Venäläinen 2008). The postponment of the start of the snow season in late autumn due to rising temperatures can also be considerable (Ruosteenoja et al. 2011, Räisänen & Eklund 2012). However, this does not necessarily have an increasing effect on the number of fires or the burnt area because long-lasting frontal type rain events typically become more frequent during the autumn (while shower-type rainfall correspondingly becomes less frequent than in summertime) due to the shortening of the daylight period, evaporation also decreases and the formation of dew is enhanced, with all these factors lowering the proneness of vegetation to fire (Tanskanen & Venäläinen 2008). Kilpeläinen et al. (2010) concentrated on the annual changes in forest fire potential and found that, based on changes in temperature, precipitation and evaporation, the number of fire alarm days would increase in southern Finland by 30 to 60 d (from the current 60 to 100 d) and in the north by 30 to 36 d (from the current 15 to 20 d) by the end of the 21st century. Their results were based on the pessimistic SRES A2 emission scenario. According to Kilpeläinen et al. (2010), the highest values of forest fire potential in the future, 160 d, were found in the southernmost parts of the country, corresponding to as much as >5 mo altogether.

The FDD models applied in this study include many simplifications. First, in addition to mean temperature and precipitation, other meteorological parameters such as relative humidity, potential evaporation and wind speed also affect the fire danger. However, when the method is applied to the future climate, the requisite input data is not necessarily available at the required resolution. In this study, we wanted to apply the probabilistic approach, and therefore settled for the mean climatic variables only. Additionally, other climatological factors besides observations of the basic meteorological variables could give important information relating to forest fire activity. For example, Macias Fauria & Johnson (2008) found that in the boreal forests of North America, mid-tropospheric blocking highs causing rapid fuel drying and contributed significantly to the yearly area burned.

Second, by using the same regression models for the reference period and for the future calculations, we assume that the relations between the summertime mean temperature and precipitation, as well as between the average summertime climate and the number of FDDs, remain the same from the 1960s until the end of the 21st century. By definition, in each of the study areas, the FDD models are the best fits to the climate of the reference period. However, the FDD models were found to even out the probability distributions of FDDs in the reference period: the models both overestimated the minima and underestimated the maxima (Fig. 2). Based on the results, the number of FDDs in the future is greater than in the reference period, which means that, according to Fig. 2, the FDD climate is shifting towards an area in which the regressions tend to underestimate the number of FDDs. This result suggests that there might actually be more FDDs in the future than indicated by the present results.

Third, we assumed that the summertime precipitation climate type in Finland at the end of the 21st century is similar to that of the reference period. The temporal and spatial distribution of summertime precipitation crucially controls forest fires. It is not only the amount of precipitation but also the frequency of precipitation that is significant for fire activity. Long-lasting, frontal type rain events wet soil and forest stands effectively, whereas short but intensive showers contribute more to surface runoff. Although in general the precipitation amounts show a tendency to increase towards the end of the century, the actual number of rainy days will not necessary increase in summer, and the length of dry spells might even get longer (Jylhä et al. 2009, Lehtonen et al. 2014b). Thus, the increasing precipitation totals would be a consequence of intensifying downpours (Lehtonen et al. 2014b). The increasing inter-annual variability of summertime precipitation (Giorgi & Coppola 2009, Heinrich & Gobiet 2012) could arise from the precipitation climate becoming more changeable and might in fact increase the number of summers with high forest fire danger. Information on future precipitation at a daily resolution would enable the classification of fire danger events that last longer than 1 d and vary in severity.

Fourth, we also assumed the fire proneness of the surroundings to remain the same for the whole study period. However, the rising temperatures and changes in precipitation amounts may well lead to changes in forest stand types, their area and the amount and characteristics of the fuel. For example, significant changes in tree species composition of forest stands and enhanced tree growth due to warming climate have been detected, e.g. by Kellomäki et al. (2008) and Peltola et al. (2010). According to these authors, forest growth will increase, especially in northern Finland. Also, MacDonald et al. (2008) discussed the advance of the treeline into current tundra areas, and Jylhä et al. (2010) projected movements of the borderlines between boreal and tundra climate types. These results imply that climate change could indirectly affect the regional patterns of fire danger.

The uncertainties in the FDD model add to those of future climate change. Therefore, the total uncertainty in the change in forest fire danger is most probably larger than the PDFs alone would suggest. According to the median estimates, however, the future mean summertime climate in Finland favours forest fire occurrence more than today's climate does. Yet the number and size of forest fires are always related to a combination of several factors, climate and prevailing weather being just one of them. Human behaviour is one of the most important factors contributing to the ignition and spreading of forest fires (Wallenius 2008, 2011). For example, Wallenius (2011) found that the steep decline in forest fires about a century ago in coniferous forests could not be connected to any climatological forcing but most likely to changes in human behavior. In Eurasia, especially in Fennoscandia, intensive forest management controls the state of forests and thereby defines the characteristics of available fuel in forests (Kellomäki et al. 2008). Changes in the number of FDDs and fire potential driven by climate do not necessarily transfer to the number of fires as such. Further, possible future increases in climate-driven forest fire danger would probably lead to intensification of fire management, and the final conclusion of the effect of the increasing FDDs may be hard to reach. The number of fires ignited under similar climatic conditions varies according to time and location. Socio-economical changes will have a major impact not only on the future fire danger or risk, but also on the actual number of fires ignited.

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