Nat. Hazards Earth Syst. Sci., 12, 2591–2601, 2012
www.nat-hazards-earth-syst-sci.net/12/2591/2012/
doi:10.5194/nhess-12-2591-2012

Natural Hazards
and Earth
System Sciences

Long-term temporal changes in the occurrence of a high forest fire danger in Finland

H. M. Mäkelä, M. Laapas, and A. Venäläinen

Finnish Meteorological Institute, Climate Change Research Unit, P.O. Box 503, 00101 Helsinki, Finland

Correspondence to: H. M. Mäkelä (hanna.makela@fmi.fi)

Received: 8 March 2012 – Revised: 25 May 2012 – Accepted: 18 June 2012 – Published: 16 August 2012

Abstract. Climate variation and change influence several ecosystem components including forest fires. To examine long-term temporal variations of forest fire danger, a fire danger day (FDD) model was developed. Using mean temperature and total precipitation of the Finnish wildfire season (June–August), the model describes the climatological preconditions of fire occurrence and gives the number of fire danger days during the same time period. The performance of the model varied between different regions in Finland being best in south and west. In the study period 1908–2011, the year-to-year variation of FDD was large and no significant increasing or decreasing tendencies could be found. Negative slopes of linear regression lines for FDD could be explained by the simultaneous, mostly not significant increases in precipitation. Years with the largest wildfires did not stand out from the FDD time series. This indicates that intra-seasonal variations of FDD enable occurrence of large-scale fires, despite the whole season's fire danger is on an average level. Based on available monthly climate data, it is possible to estimate the general fire conditions of a summer. However, more detailed input data about weather conditions, land use, prevailing forestry conventions and socio-economical factors would be needed to gain more specific information about a season's fire risk.

1 Introduction

A forest fire is a consequence of three elements: suitable weather conditions, flammable fuel load and an igniter (e.g. Pyne, 2001). Currently, fire in boreal forests is typically human-ignited and the other main cause is a lightning strike (Wallenius, 2008). Fire has traditionally been an important natural factor contributing to the development and structure of the northern boreal forests (e.g. Zackrisson, 1977).

Weather and climate play a critical role in setting the conditions favourable for a forest fire. High temperatures and low relative humidities combined with strong wind intensify evaporation, dry up the soil and turn it easily flammable. Prolonged periods with high temperatures and no rain correlate well with periods of high forest fire danger. Prevailing dry conditions affect the flammability of particularly dead forest fuel, whose moisture content is already low compared to live fuel (Tanskanen and Venäläinen, 2008; and references therein).

Finland belongs to the boreal vegetation and climate zone where the forest fire season is relatively short starting after snowmelt in April and ending in September. During the latest decades, there have been approximately 950 forest fires annually with an average size of 0.5 ha (Finnish Forest Research Institute, 2010). In addition to forest fires, also wildfires, including e.g. grassland and bushes, cause many rescue operations every year (Finnish Rescue Service database PRONTO). Active monitoring of fires keeps the annually burnt area small even though the number of fires is quite high (Finnish Ministry of Agriculture and Forestry, 2007). The wide forest areas in Finland are intersected by numerous forest truck roads that control the spreading of the fires for their part and enable effective fire extinction also.

Even though the fires are small in general, there are occasions when long dry periods enable very large fires. The largest wildfire on the record in Finland occurred in 1960 in Tuntsa area in eastern Lapland where about 20 000 ha of spruce dominant forest were burned in a widespread forest fire. The fire continued spreading over the borders to

Russia damaging more than 100 000 ha of forest there. Large wildfires are common in Russia where many million hectares of forest may burn during a typical summer (Vivchar, 2011). If the conditions are favourable for fire activities, the burned area may increase to tens of millions of hectares (Vivchar, 2011). These figures reflect the magnitude of the potential destruction possible in the boreal forests of Northern Europe in suitable conditions. In Finland, other significant conflagrations have occurred in 1959 in Isojoki-Honkajoki and in 1970 in Kalajoki, both in western Finland. Both events affected an area of about 1700 ha. In both cases, weather (especially varying winds) played an important role in hampering the fire extinction.

The possibility of large fires is very much dependent on the weather conditions. A long period with no rain and high wind speed is needed. Venäläinen et al. (2009) estimated that at some arbitrary location in Finland approximately once in ten years a 40-day period with at most 10 mm of accumulated rain is likely. According to fire statistics, these dry conditions even triple the number of fires occurring during a fire season. However, when we want to study long time series, not always are all the needed meteorological parameters available. Nevertheless, typically precipitation and temperature data are available, at least on a monthly scale, and they can explain most of the fire danger.

In Finland there is a long tradition in forest research, and also the occurrence of forest fires has been recorded and studied since the late 19th century (Saari, 1923; Laitakari, 1960). In his profound study, Saari (1923) proposes that the most significant controlling weather factor of the forest fire danger is drought. The weather parameters affecting the development of a drought are precipitation, evaporation and soil moisture. The negative correlations between the amount of rainfall during the summer months and both the number of fires and the total burned area were noticeable, the former correlation being somewhat higher than the latter. Already Saari (1923) pointed out that more fires and a greater burned area can be expected during warmer summers than during the colder ones. Thus, according to Saari (1923), the increase in the risk of forest fire depends partly upon a rise in the mean temperature, and partly upon a decreasing amount of rainfall, so that the rain amounts have a greater effect on the yearly fire danger variation than the temperature.

Long-term changes in forest fire danger could presumably follow, more or less, changes in climate. Temperatures in Finland are known to have increased during the latest 160 yr, spring being the season where the long-term warming is strongest (Tuomenvirta, 2004; Tietäväinen et al., 2010). Future temperatures are projected to increase particularly in winter, summertime warming being more modest though considerable (Jylhä et al., 2009). According to Jylhä et al. (2009), summers will get 1–5 °C warmer than during the period 1971–2000 by the end of this century. Due to the large year-to-year variation, there can hardly be found any clear trends in the summertime precipitation in the past climate, but for the future climate, models predict an increase in precipitation during summer months (e.g. Ylhäisi et al., 2010). Thus, projections of the future climate show indications both for increasing fire danger due to increasing temperatures and for decreasing fire danger due to increasing precipitation. Whether the fire danger will increase or decrease depends strongly on the temporal and spatial distribution of the summertime precipitation. Kilpeläinen et al. (2010) found out that the annual frequency of forest fires over whole Finland will increase by about 20 % by the end of this century compared to the present day. The increase of the fire potential was more pronounced in the southern than the northern part of the country.

Fire danger can nowadays be estimated in advance by means of different fire potential models that produce indices of the risk of a fire. In Finland, the national weather service follows operationally conditions favourable for forest fires using a fire danger index called Finnish Forest Fire Index (FFI) (Vajda et al., 2012; Heikinheimo et al., 1998; Venäläinen and Heikinheimo, 2003). The most commonly used method for evaluating forest fire danger in Europe and North America is the so-called Canadian Forest Fire Danger Rating System (CFFDRS) from the late 1960s (Van Wagner, 1987). According to Vajda et al. (2012), these two fire danger evaluation systems give consistent results about the fire danger in Finland especially during the high fire season. Though forest fire danger indices would give a good assessment on the long-term temporal variation of fire potential, they can be used very seldom only because the needed detailed meteorological input data are rarely available. That is why the long-term fire danger assessments must rely on more simple but available data. Typically, this means monthly, sometimes daily, mean temperatures and precipitation values. As well, the observation network used to be very sparse and thus the spatial coverage has been very coarse. With meteorological and/or climatological input data, one can assess the probability of a forest fire from the viewpoint of weather-related factors. Forest fire danger indices based on this kind of data give an evaluation of prevailing fire danger. Inclusion of causative agents such as human action and vulnerability of the environment expands the concept of fire danger into fire risk (e.g. Hardy et al., 2005; NWCG, 2011).

The main objective of this study is to examine the long-term temporal variation of forest fire danger in Finland with emphasis on the extreme fire danger conditions. In this study, long, gridded, climate data sets of monthly mean temperature (Tietäväinen et al., 2010) and precipitation sums (Ylhäisi et al., 2010) in Finland starting from the early 20th century are combined with the time series of the Finnish forest fire index starting from the 1960s. Based on the regional correlations between the fire danger data and the climate data, a fire danger day (FDD) model will be developed. Using the model, the seasonal number of forest fire danger days in the first half of the 20th century will be estimated. Extreme value analysis methods are applied to the modelled forest fire

Table 1. Scaling of the volumetric moisture content (%) into classes of surface wetness and forest fire index (FFI). Table adapted from Vajda et al. (2012).

Index	Volumetric moisture (%)	Moisture status
6.0	10	Very dry
5.9–5.0	11–14	Dry
4.9–4.0	15–19	Moderately dry
3.9–3.0	20–25	Moderately wet
2.9–2.0	26–32	Wet
1.9–1.0	33–50	Very wet

danger time series to investigate the occurrence of the highest fire danger conditions. The results of the study can give new insight on the role of fire as one key element in the Finnish forest ecosystem. The planning of rescue services may also benefit from the information concerning the long-term variation of fire danger.

2 Material and methods

2.1 Assessment of forest fire danger

In this study, we assessed the forest fire danger based on a forest fire danger index called Finnish forest fire index (FFI). The FFI value describes essentially the moisture content of a soil surface layer. For computation of the index, volumetric moisture of a 60-mm-thick soil surface layer is estimated using evaporation and precipitation data (Vajda at al., 2012; Venäläinen and Heikinheimo, 2003; Heikinheimo et al., 1998). Estimation of the actual evaporation from the surface is done using potential evaporation, which is calculated from routine weather observations with the so-called Penman-Monteith equation (Monteith, 1981), and drying efficiency describing the ability of a surface to evaporate in certain atmospheric conditions. Details of the calculation of the index are described in Vajda et al. (2012).

The follow-up of the soil moisture starts immediately after the snow has melted in spring. The volumetric moisture content is estimated to be at maximum 50 % and at minimum 10 % (Heikinheimo et al., 1998), corresponding to FFI values of 1 (the lowest possible fire danger) and 6 (the highest possible fire danger), respectively (Table 1). A forest fire warning is put out if FFI equals 4 or more. In Finland, an average fire season starts in April and ends in September.

The fire index data we used for this study consisted of daily values of FFI collected from 36 weather stations located around Finland (Table 2, Fig. 1). The FFI data covered at most of the stations years 1961–1997. For some stations, the data coverage period was shorter (Table 2). After 1997, calculation of the fire index was changed into a grid-based routine. For this study, we used only station-wise FFI data.

Table 2. Regions and observation stations with FFI data used in the study.

	Region	Observation stations with FFI data	Data period
1	Uusimaa	Hanko	1961–1997
		Inkoo	1963–1997
		Helsinki	1985–1997
		Vantaa	1961–1997
2	Finland Proper	Suomusjärvi	1988–1997
3	Satakunta	Pori	1961–1997
		Rauma	1961–1996
		Kankaanpää	1961–1997
4	Tavastia Proper	Jokioinen	1961–1997
5	Pirkanmaa	Pirkkala	1980–1997
		Jämsä	1964–1997
6	Päijänne Tavastia	Lahti	1961–1997
7	Kymenlaakso	Kotka	1961–1997
		Kouvola	1961–1997
8	South Karelia	No stations	
9	Southern Savonia	Mikkeli	1961–1997
10	Northern Savonia	Kuopio	1961–1997
11	North Karelia	Ilomantsi	1961–1997
12	Central Finland	Viitasaari	1970–1997
13	Southern Ostrobothnia	Ähtäri	1961–1997
14	Ostrobothnia	Vaasa	1961–1994
		Valassaaret	1961–1997
		Pietarsaari	1964–1991
15	Central Ostrobothnia	No stations	
16	Northern Ostrobothnia, east	No stations	
17	Northern Ostrobothnia, west	Nivala	1965–1997
		Hailuoto	1961–1997
		Pudasjärvi	1961–1997
18	Kainuu	Kajaani	1961–1997
		Suomussalmi	1971–1997
19	Lapland	Kemi	1961–1994
		Pello	1971–1997
		Rovaniemi	1961–1997
		Sodankylä	1961–1997
		Salla	1961–1997
		Muonio	1962–1997
		Kilpisjärvi	1980–1997
		Ivalo	1961–1997
20	Åland Islands	Jomala	1961–1995

From the daily FFI data, we calculated the number of days with high forest fire danger (fire danger day = FDD) during the main forest fire season from June to August when most of the fires take place. We used two thresholds:

FDD4 = number of days when FFI equals 4 or more;

FDD5 = number of days when FFI equals 5 or more.

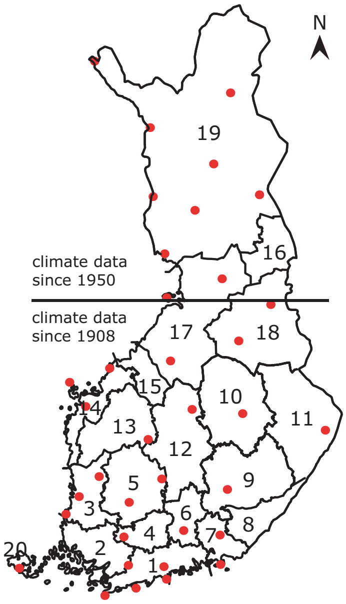

Fig. 1. Study regions are numbered from 1 to 20. Red dots mark the locations of the observation stations with FFI data. South of the horizontal line climate data start in 1908 while north of the line not until 1950.

After calculating the FDD4 and FDD5 values for each year and station, we interpolated the station values into a 10 km grid using a spatial interpolation method called kriging (e.g. Ripley, 1981). Regional FDD values were then calculated for 20 regions separately (Fig. 1) by averaging all the grid points in a region.

2.2 Climate data

Climate data consisted of gridded monthly mean temperatures (Tietäväinen et al., 2010) and monthly precipitation sums (Ylhäisi et al., 2010). The gridded climate data have been produced by interpolating station values of monthly mean temperature and precipitation sums from Finnish weather stations, and from selected stations in Sweden, Norway and Russia near the Finnish border to a 10 km grid using a spatial interpolation method called kriging (e.g. Ripley, 1981; for climatological studies in Finland, Henttonen, 1991).

Gridded monthly precipitation data extend in the southern part of Finland back to the year 1908. In northern Finland, gridded precipitation data do not start until 1950 because of the lower station density. Monthly mean temperature grids were collected for the same time periods as the precipitation data. Regional values for June–August mean temperatures and precipitation sums were then calculated from the gridded climate values by averaging all the grid points in a region. By choosing interpolated climate data instead of station values, we were able to extend the time series of the estimated number of forest fire danger days as far back in time as possible. There are only few weather stations with FFI data that were operational already in the early decades of the 20th century.

2.3 Estimation of the number of the fire danger days

We assumed that the summertime number of the fire danger days (FDD) has linear dependence on temperature (T) and precipitation (P) of the same period:

$$\mathrm{FDD} = a * \mathrm{X}_T + b * \mathrm{X}_P + c. \tag{1}$$

The dependence was assumed to remain the same for the whole study period 1908–2011. Higher temperatures and lower precipitation amounts lead to more days with forest fire danger, and vice versa. The suitability of this relationship varied between the regions (Fig. 2). We fitted simple linear regression functions to the FDD and climate data in each of the regions separately during the overlapping data period from 1961 to 1997. By using the obtained regression models and the gridded climate data, we then estimated the number of fire danger days for the years 1908–2011 in southern Finland. Because of the shorter climate data series in northern Finland, the number of fire danger days for the regions 16–19 was possible to estimate only starting from the mid-20th century.

2.4 Extreme value analysis

Extreme value analysis of fire danger days was performed for the southern regions with climate data starting from 1908 (regions 1–15 and 20; see Fig. 1). For the extreme value analysis, the regional FDD values were averaged over all the 16 regions instead of performing the analysis for each of the regions separately. For the northern regions (16–19), no extreme analysis was performed due to the shorter FDD time series starting in 1950 and the somewhat poorer data quality according to the determination coefficients of the regression models (see Sect. 3.1).

Extreme value analysis of the fire danger days was performed by using the R statistical computing environment and especially the R-based Extremes Toolkit software (Gilleland and Katz, 2005). Extreme analyses were carried out by maximum likelihood fitting of studied data sets to GPD (General Pareto Distribution) models (Coles, 2001). The GPD approach was chosen considering the nature of fire danger data with yearly values, rather than block maxima approach and GEV (Generalized Extreme Value) distribution that are more suitable for daily values. In the GPD approach used here, the part of the data exceeding a given threshold is fitted to the GPD distribution. Choosing the right threshold is important as a threshold that is too low will give biased GPD parameter estimates, but a threshold that is too high will result in large variance of GPD parameter estimates (Gilleland and Katz, 2005). The Extremes Toolkit provides two plotting tools for

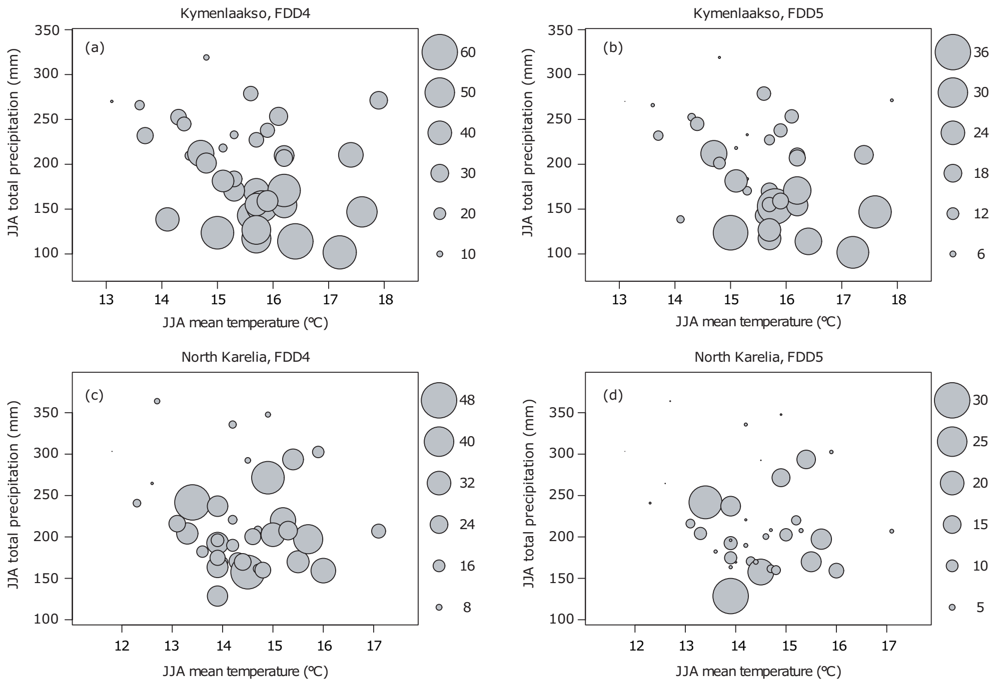

Fig. 2. Scatter plots of June–August mean temperature, June–August total precipitation and the number of the fire danger days calculated from the observed FFI in 1961–1997 in Kymenlaakso **(a)** for FDD4 and **(b)** for FDD5 and in North Karelia **(c)** for FDD4 and **(d)** for FDD5. Scales on the right side of each plot show the number of fire danger days corresponding to the size of the circles: a larger circle indicates more fire danger days.

threshold selection, both used here. These are mean residual life plots and methods that fit data to a GPD over a range of thresholds. Even with these descriptive tools, it should be kept in mind that choosing a threshold is in the end a subjective process.

The maximum likelihood estimates (MLE) and the 95 % confidence intervals, based on profile likelihood method (Coles, 2001), of return levels of the annually totalled FDD4 and FDD5 were calculated for 5, 10, 20, 50, 100, 200 and 500-yr return periods.

3 Results

3.1 Number of estimated fire danger days based on monthly climate data

For FDD4, the determination coefficient of the regression (R-squared) varied from 0.251 in North Karelia to 0.766 in Kymenlaakso being on average 0.589. For FDD5, the R-squared varied from 0.124 in North Karelia to 0.610 in Uusimaa being on average 0.408 (Table 3). Both for FDD4 and FDD5, the lowest values of the determination coefficient were found in eastern Finland in North Karelia and the eastern part of Northern Ostrobothnia. The highest values of the determination coefficients were found in both cases in the southern and coastal regions (Fig. 3). For FDD5, the coefficients of determination were for every region lower than for FDD4. In the easternmost part of the country, the correlations were very low: in North Karelia only 0.124 and in the eastern part of Northern Ostrobothnia 0.170.

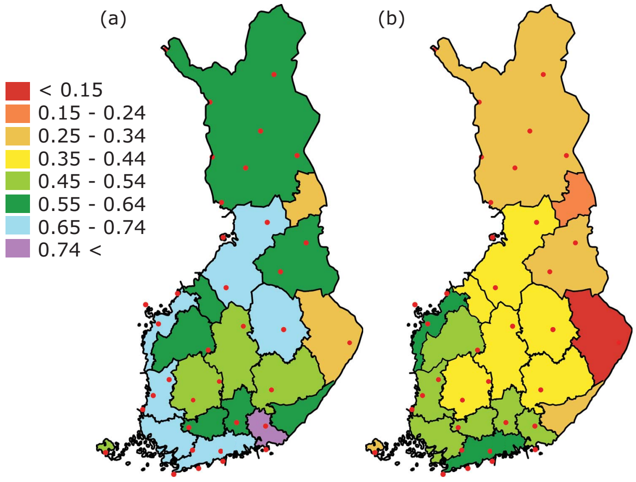

Fig. 3. The coefficient of determination (R^2) of the linear multi-regression models for **(a)** FDD4 and **(b)** FDD5. The red dots mark the locations of the observation stations with FFI data.

The estimated FDD data show that there was a lot of year-to-year variation. During the latest normal period 1981–2010, the number of fire danger days varied between 13–44 (FDD4) and 3–23 (FDD5); the least days occurred in

Table 3. The linear multi-regression functions and the coefficients of determination (R^2) for FDD4 and FDD5 for each of the regions. Minimum and maximum values of R^2 are in bold.

		FDD4		FDD5	
	Region	Regression function	R^2	Regression function	R^2
1	Uusimaa	$4.13x_T - 0.18x_P + 6.75$	0.713	$2.99x_T - 0.11x_P - 7.48$	**0.610**
2	Finland Proper	$3.16x_T - 0.18x_P + 24.67$	0.668	$3.09x_T - 0.11x_P - 7.21$	0.501
3	Satakunta	$2.83x_T - 0.19x_P + 29.02$	0.657	$2.70x_T - 0.12x_P + 1.06$	0.491
4	Tavastia Proper	$4.86x_T - 0.15x_P - 13.02$	0.597	$3.12x_T - 0.09x_P - 16.10$	0.480
5	Pirkanmaa	$3.38x_T - 0.14x_P + 6.96$	0.546	$2.26x_T - 0.07x_P - 5.24$	0.416
6	Päijänne Tavastia	$3.59x_T - 0.17x_P + 7.99$	0.616	$2.33x_T - 0.08x_P - 7.39$	0.485
7	Kymenlaakso	$3.77x_T - 0.20x_P + 14.63$	**0.766**	$2.55x_T - 0.11x_P - 1.54$	0.540
8	South Karelia	$3.17x_T - 0.15x_P + 8.86$	0.580	$1.32x_T - 0.08x_P + 6.62$	0.337
9	Southern Savonia	$3.64x_T - 0.13x_P - 3.23$	0.546	$1.61x_T - 0.06x_P - 3.38$	0.378
10	Northern Savonia	$3.87x_T - 0.17x_P + 5.34$	0.687	$1.93x_T - 0.09x_P - 1.01$	0.417
11	North Karelia	$3.18x_T - 0.07x_P - 7.65$	**0.251**	$0.73x_T - 0.04x_P + 7.42$	**0.124**
12	Central Finland	$2.95x_T - 0.13x_P + 6.83$	0.544	$1.58x_T - 0.05x_P - 3.41$	0.385
13	Southern Ostrobothnia	$1.83x_T - 0.17x_P + 35.47$	0.623	$0.91x_T - 0.11x_P + 20.24$	0.520
14	Ostrobothnia	$1.51x_T - 0.23x_P + 55.63$	0.651	$0.99x_T - 0.17x_P + 32.79$	0.555
15	Central Ostrobothnia	$1.61x_T - 0.19x_P + 40.79$	0.630	$0.99x_T - 0.10x_P + 16.79$	0.444
16	Northern Ostrobothnia, east	$3.12x_T - 0.08x_P - 9.74$	0.318	$1.34x_T - 0.02x_P - 10.08$	0.170
17	Northern Ostrobothnia, west	$2.02x_T - 0.20x_P + 36.29$	0.650	$1.15x_T - 0.10x_P + 12.91$	0.398
18	Kainuu	$3.04x_T - 0.16x_P + 12.33$	0.632	$1.48x_T - 0.05x_P - 2.98$	0.307
19	Lapland	$2.97x_T - 0.12x_P + 6.25$	0.563	$1.02x_T - 0.04x_P + 0.21$	0.320
20	Åland Islands	$4.00x_T - 0.19x_P + 14.28$	0.549	$4.04x_T - 0.10x_P - 20.08$	0.275

the northeastern part of the country and most days in the southwest (Fig. 4). Thus, the days with fire danger (FDD4) accounted on average for 25–48 % of all the days during one season (June–August). The proportion of the days with very high fire danger (FDD5) was on average 3–14 % of all the days. Slopes of linear regression lines fitted for the annual number of fire danger days in 1908–2011 decreased in majority of the regions. However, none of the trend lines were statistically significant according to the simple t-test. At the same time, there was a significant increase (p-value < 0.05) in June–August mean temperature in all regions except in Lapland (region 19). For precipitation, the linear regression lines decreased in all regions, but the slopes were statistically significant only in less than half of them.

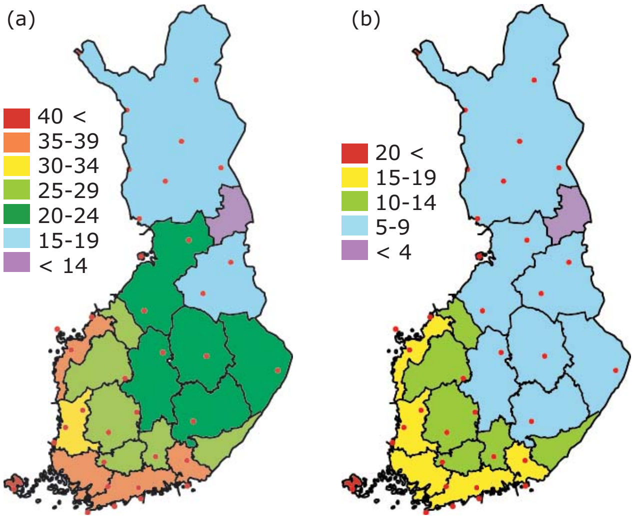

Fig. 4. The average number of the fire danger days in 1981–2010 for **(a)** FDD4 and **(a)** FDD5. The red dots mark the locations of the observation stations with FFI data.

Figures 5 and 6 give examples of the time series of the estimated number of fire danger days in Kymenlaakso and North Karelia, where the regression models performed the best and the poorest, respectively. The simple linear model of FDD tended to underestimate the very high values and overestimate the very low values of fire danger days compared to the observed numbers. This feature was emphasized in the FDD5 time series where the relationship between the climate and FDD data was generally weaker.

Year-to-year variation of FDD5 followed closely to that of FDD4 in each of the regions. The annual number of the FDD5 was on average 39 % of all the fire danger days (FDD4). The proportion of FDD5 to FDD4 was the largest in the southwestern regions (47–51 % in Satakunta, Finland Proper and the Åland Islands) and the lowest in the northeast (25–27 % in the eastern part of the Northern Ostrobothnia and in Lapland).

The average number of FDD4 and FDD5 for the southern part of the country (regions 1–15 and 20) was on average 29 and 13, respectively, in 1981–2010 (Fig. 7). The linear slopes for FDD4 and FDD5 calculated over the whole study period 1908–2011 decreased but statistically not significant.

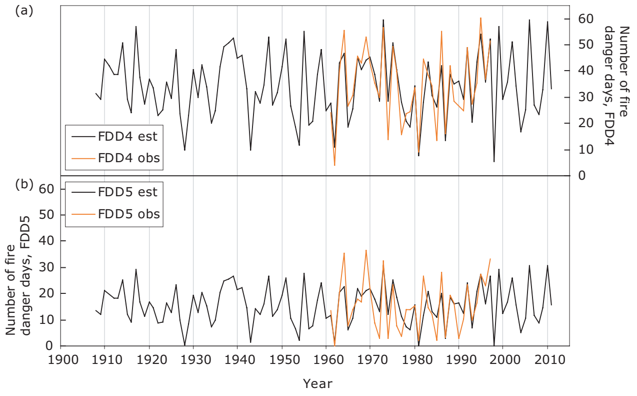

Fig. 5. Estimated number of fire danger days (black line) in Kymenlaakso **(a)** FDD4 and **(b)** FDD5 in 1908–2011. Red line shows the calculated number of the fire danger days based on the FFI data in 1961–1997.

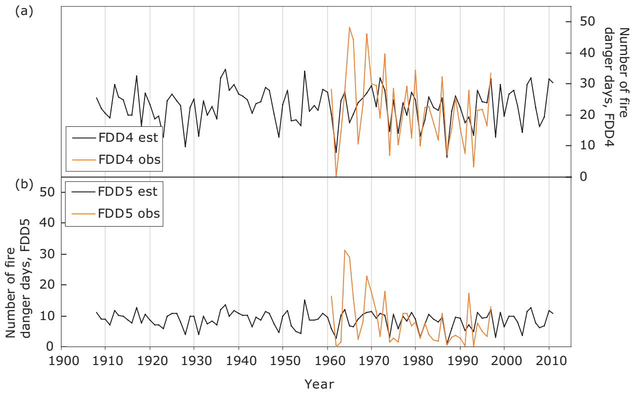

Fig. 6. Estimated number of fire danger days (black line) in North Karelia **(a)** FDD4 and **(b)** FDD5 in 1908–2011. Red line shows the calculated number of the fire danger days based on the FFI data in 1961–1997.

Year-to-year variations were large also for the averaged FDD. Theoretical maximum number of fire danger days during one season would be 92. Thus, the average number of the FDD4 (FDD5) accounts for 32 % (14 %) of the maximum. The least fire danger days occurred in 1981 and 1998, which were the two rainiest seasons, whereas the driest seasons 1955, 2006 and 1917 led to the largest numbers of fire danger days (Fig. 7). The proportion of the days with very high fire danger (FDD5) to all fire danger days (FDD4) was the largest, 50 %, in 2006 and 1937, which were both very warm and dry.

In northern Finland, in 1950–2011, number of fire danger days has varied from 0 (0) to 39 (14) for FDD4 (FDD5). In 1981–2010, the average FDD4 (FDD5) was 18 (6). In 1981, which was the rainiest summer with precipitation amount 55 % above the average, there existed no fire danger days during June–August. The most fire danger days existed in 2006, 1969 and 1980. These seasons were also the driest ones.

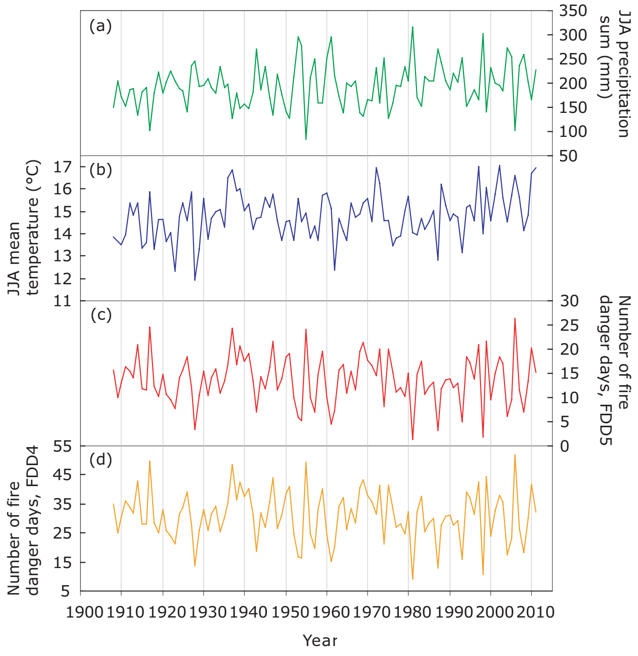

Fig. 7. June–August **(a)** precipitation sum, **(b)** mean temperature, and the average number of the estimated fire danger days for **(c)** FDD4 and **(d)** FDD5 in the southern study area (regions 1–15 and 20) in 1908–2011.

3.2 Extreme value analysis

The maximum likelihood estimates (MLE) of return levels of the annual number of the averaged FDD4 and FDD5 ranged from 39 to 52 and from 18 to 26 for FDD4 and FDD5, respectively, for the return periods of 5 to 500 yr (Table 4). The upper confidence interval of return level of FDD4 for return period of 500 yr reached 59 being 64 % of the theoretical maximum (92 days). The upper and lower confidence intervals of the return levels of the fire danger days were asymmetrically distributed around the maximum likelihood estimate, the lower confidence interval being narrower than the upper interval (Fig. 8). The GPD model systematically underestimated the return levels of FDD4 and FDD5 for the longest return periods. However, all the FDD values remained within the confidence intervals (Fig. 8).

4 Discussion and concluding remarks

The number of fire danger days during the main Finnish wildfire season can, to some extent, be estimated based on the mean temperature and total precipitation of the same period. Consideration of temperature and precipitation data on a higher time scale, and inclusion of other variables, such as relative humidity, wind speed, or different indices related to drought, would have been needed to improve the analysis. For example, a heavy shower may contribute significantly

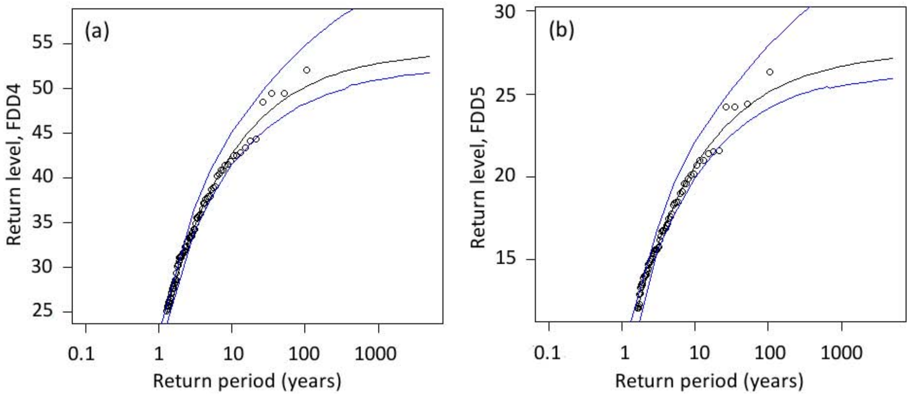

Fig. 8. Return level plots of **(a)** FDD4 and **(b)** FDD5 for 1908–2011. Black curve denotes maximum likelihood estimate of return level against different return periods. Blue curves are 95 % confidence limits of return levels based on the profile likelihood method.

Table 4. Maximum likelihood estimates (MLE) of return levels of FDD4 and FDD5 for 5, 10, 20, 50, 100, 200 and 500-yr return periods based on data from period 1908–2011. Upper and lower confidence intervals (CI), the used data threshold (u) for GPD fitting and the proportion of data exceeding the threshold (Rate) are presented also.

FDD4 (u = 25, Rate = 78.8 %)							
Return period	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr
Upper CI	40.8	45.1	48.5	52.4	54.8	56.9	59.1
MLE	38.5	42.7	45.8	48.6	50.2	51.3	52.3
Lower CI	37.5	41.5	44.2	46.9	48.3	49.3	50.5

FDD5 (u = 12, Rate = 62.5 %)							
Return period	5 yr	10 yr	20 yr	50 yr	100 yr	200 yr	500 yr
Upper CI	19.5	22.1	24.1	26.4	27.9	29.2	30.7
MLE	18.2	20.7	22.5	24.2	25.1	25.7	26.3
Lower CI	17.7	20.0	21.7	23.3	24.1	24.7	25.3

to a month's precipitation sum even though for most of the month dry weather prevails. Comparison of the number of fire danger days with number of precipitation days would also likely improve the analysis. However, time series of the foregoing parameters are rather short, starting not until the 1960s. That is why, in order to obtain longer time series, we had to base the analyses on monthly temperature and precipitation data sets, which are as such reasonably adequate but by no means optimal for the approach.

The relationship between the fire season's mean temperature, precipitation sum and number of fire danger days was assumed to remain the same for the whole study period 1908–2011. At the same time, anthropogenic climate warming has affected Finland's climate by increasing mean temperatures (Tietäväinen et al., 2010). As for precipitation amounts, temporal changes are not easy to detect and they are mostly not significant (Ylhäisi et al., 2010). However, despite the different changes in summertime mean temperature and precipitation sum in the past, the summertime climate type itself in Finland has not changed. So far, there cannot be seen any significant changes in the summertime precipitation patterns in Finland, e.g. the number of dry days has remained the same for the whole 20th century (Heino, 1994). The 36-yr-long time period (1961–1997) from which the regression model between the climate variables and number of fire danger days was derived from represents well the 20th century summertime climate in Finland in general. All kinds of summers existed during that period: dry and wet, cool and hot.

Based on this climatological study, the fire proneness of the Finnish forests has not changed significantly during the last 100 yr even though at the same time the increase in the forest fire season's mean temperature was statistically significant. So, it seems that the simultaneous increase, albeit statistically mostly not significant, in precipitation sum has compensated the increased mean temperatures. Thus, the large natural year-to-year variations of precipitation and number of fire danger days still override their systematic changes, if there would be any. Based only on seasonal values of temperature and precipitation, we cannot really draw any conclusion of the details of the climatological changes taken place, e.g. if the changes have been uniformly distributed or if they have concentrated on the extremes. If available, this detailed information would be very helpful in considering the changes in the occurrence of the fire danger days.

The spatial and temporal distribution of the future summertime precipitation will have a major role in defining the trend of number of fire danger days in future. The increasing of the fire danger days would require longer dry periods compared to present climate. According to Jylhä et al. (2009), the most distinct feature of the future summertime precipitation climate in Finland is a growth of heavy downpours. In light of the present knowledge, it is still unclear whether the number of dry days and the length of the longest dry spells will increase or decrease. Scenarios of future precipitation are still more uncertain than those of mean temperature (Hegerl et al., 2007). In Northern Europe, climate's natural variability is large and not fully understood. Despite the on-going continuous development, global climate models are still far from capable of fully describing Earth's complex climate system and future greenhouse gas emissions also are yet unpredictable (Hegerl et al., 2007). A set of different climate models and emission scenarios will produce a large range of possible prospects for future summertime precipitation climate in Finland (Jylhä et al., 2009). Nonetheless, rising temperatures will lead to enhanced evaporation and drying of the soil and vegetation (Jylhä et al., 2009). This will, for its part, contribute to the increase of number of fire danger days.

Large recorded fires (burned area of over 1000 ha) in Finland like in Isojoki-Honkajoki (1959), Tuntsa (1960), and Kalajoki (1970) cannot be seen in the fire danger day statistics time series as any clear peak (Fig. 7). This demonstrates the intra-seasonal variation of FDD that enables the occurrence of very large-scale fires despite the whole season's fire danger is on the average level. The mean seasonal conditions describe the mean conditions like the total number of fires, but they cannot be used for the prediction of the occurrence of a single event. Naturally, if the whole season was very wet, it would make large-scale fires impossible. For example, the number of fire danger days was the lowest in 1981 and second lowest in 1998, which were also the two rainiest summers (Fig. 7). However, the driest summer 1955 did not result in the highest number of fire danger days, because the mean temperature of the summer 1955 was only on the average level. The highest number of fire danger days occurred in 2006 when the summer was not only dry but unusually warm also. The largest proportion of the very high fire danger days (FDD5) to all fire danger days (FDD4) occurred also when the season was both very warm and dry (1937 and 2006). Regionally, the proportion of FDD5 to FDD4 was the largest in the southwestern regions and the lowest in northeast. Hence, it followed the distribution of the number of fire danger days. The proportion of days with very high fire danger (FDD5) was the largest where there existed the highest number of fire danger days in general.

The best regression model fits for the relationship between the number of fire danger days and the mean temperature and total precipitation were found in the southern and western parts, while in the northeastern parts the models performed not that well (Fig. 3, Table 3). This goes together with the used station network with higher station densities in the south and the west and lower in east and north (Fig. 1). For example, in the eastern part of Northern Ostrobothnia (region 16), there were no observing stations with FFI data. The weather observation network of Finland is, in general, sparser in northern Finland than in the southern or middle part of the country. Still in the 1950s–1970s, the observing network in northern Finland was under an efficient developing phase and the station number grew by some tens of stations. This might have had an influence on the performance of the spatial interpolation method of the monthly mean temperature and precipitation sum in those regions, too. The dependence between the FDD and climate data was in this study supposed to be linear. As the obtained FDD models were discovered to smooth out the very high and low FDD values, it might be justified to study also other fittings for the data.

The success of an extreme value analysis is highly dependent on the quality of the data used. Long and well homogenized time series would be needed. Both these issues were somewhat questionable in this study, and that is why the extreme value analysis results should be regarded as only approximate. However, the chosen GPD models seemed to fit for the FDD4 and FDD5 data fairly well.

The fire proneness of a forest is dependent not only on climate and prevailing weather conditions, but also on forest type and available fuel load. There must be sufficient fuel available and it must be sensitive enough to fire. The fuel load of a forest depends among other things on the current social structures and prevailing forest handling and management conventions (e.g. Wallenius, 2008). The impact of the forest type was examined already by Saari (1923), and he found that the probability of a fire is highest on dry, firm grounds growing mostly pine (*Pinus sylvestris*) compared to moist grounds or marshes. Tanskanen et al. (2005) found that pine (*Pinus sylvestris*) dominated stands could be ignited on roughly three to four times more days than spruce (*Picea abies*) stands. The canopy characteristics, such as the canopy depth and the leaf area index, are also discovered to correlate strongly with the ignition success of the surface fuels (Tanskanen et al., 2005). In the past decades, the Finnish forest structure was very much impacted by the slash-and-burn agriculture, whereas currently the ongoing climate change is affecting the forest tree species distribution (e.g. Kellomäki et al., 2008). All these issues are unavoidably affecting the time series of the annual number of fire events and the burnt area.

Based on the available mean temperature and precipitation data, it is possible to estimate the general fire conditions of a summer, but for more detailed information about the fire season one would need more detailed input data about the weather conditions, the land use and the socio-economical factors, among others. However, the consideration of all the factors contributing to the fire proneness of the surroundings would require analyses of extensive data sets. The analyses presented here indicate only the mean climatological precondition of fire occurrence.

Acknowledgements. This study was carried out within the EU 7th FP Project FUME (grant agreement no. 243888). The Finnish Rescue Services is acknowledged for providing access to the fire statistics in the PRONTO database. Timo Heikkilä is thanked for sharing information about the conflagrations in Finland. Hilppa Gregow is thanked for her comments on the manuscript. Comments from the two anonymous referees were valuable in improving the manuscript.

Edited by: R. Lasaponara
Reviewed by: two anonymous referees

References

Coles, S.: An Introduction to Statistical Modeling of Extreme Values. Springer-Verlag, London, 208 pp., 2001.

Finnish Forest Research Institute: Finnish Statistical Yearbook of Forestry, Finnish Forest Research, Institute, 472 pp., 2010 (in Finnish with summary and captions in English).

Finnish Ministry of Agriculture and Forestry: Suomen metsät, Kestävän metsätalouden kriteereihin ja indikaattoreihin perustuen, Maa- ja metsätalousministeriön asettaman asiantuntijaryhmän loppuraportti, Maa-ja metsätalousministeriö 7/2007, 99 pp., 2007 (in Finnish).

Finnish Rescue Service database, PRONTO, http://prontonet.fi, last access: 8 December 2011.

Gilleland, E. and Katz, R. W.: Extremes Toolkit (extRemes): Weather and climate applications of extreme value statistics, Tutorial, 125 pp., 2005.

Hardy, C. C.: Wildland fire hazard and risk: Problems, definitions, and context, Forest Ecol. Manag., 211, 73–82, 2005.

Hegerl, G. C., Zwiers, F. W., Braconnot, P., Gillett, N. P., Luo, Y., Marengo Orsini, J. A., Nicholls, N., Penner, J. E., and Stott, P. A.: Understanding and Attributing Climate Change, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Heikinheimo, M., Venäläinen, A., and Tourula, T.: A soil moisture index for the assessment of forest fire potential in the boreal zone, EUR 18328-COST 77, 79, 711, in: Proceedings of the international symposium on applied agrometeorology and agroclimatology, edited by: Dalezios, N. R., 549–555, 1998.

Heino, R.: Climate in Finland during the period of meteorological observations, Finnish Meteorological Institute Contributions, No. 12, 209 pp., 1994.

Henttonen, H.: Kriging in Interpolating July Mean Temperatures and Precipitation Sums, Reports from the Department of Statistics University of Jyväskylä, Finland, no. 12, 41 pp., 1991.

Jylhä, K., Ruosteenoja, K., Räisänen, J., Venäläinen, A., Tuomenvirta, H., Ruokolainen, L., Saku, S., and Seitola, T.: The changing climate in Finland: estimates for adaptation studies, ACCLIM project report 2009, Finnish Meteorological Institute, Reports 2009:4, 102 pp., 2009 (in Finnish abstract, extended abstract and captions for figures and tables also in English).

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K. T., and Strandman, H.: Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management, Philos. T. Roy. Soc. B, 363, 2339–2349, 2008.

Kilpeläinen, A., Kellomäki, S., Strandman, H., and Venäläinen, A.: Climate change impacts on forest fire potential in boreal conditions in Finland, Climatic Change, 103, 383–398, 2010.

Laitakari, E.: Metsähallinnon vuosisataistaival 1859–1959, Metsähallitus, Helsinki. Silva Fenn., 107, 447 pp., 1960 (in Finnish).

Monteith, J. L.: Evaporation and surface temperature, Q. J. R. Meteorol. Soc., 107, 1–27, 1981.

NWCG (National Wildfire Coordinating Group): Glossary of Wildland Fire Terminology, http://www.nwcg.gov/pms/pubs/pubs.htm., 2011.

Pyne, S. J.: Fire – a brief history. University of Washington Press, Seattle & London, 204 pp., 2001.

Ripley, B. D.: Spatial Statistics, John Wiley & Sons, New York, 255 pp., 1981.

Saari, E.: Kuloista etupäässä Suomen valtionmetsiä silmällä pitäen, Suomalaisen Krjallisuuden Seuran kirjapainon O.Y., Helsinki, 155 pp., 1923 (Forest fires in Finland with special reference to state forests, in Finnish with a summary and captions in English).

Tanskanen, H. and Venäläinen, A.: The relationship between fire activity and fire indices at different stages of the growing season in Finland, Boreal Environ. Res., 13, 285–302, 2008.

Tanskanen, H., Venäläinen, A., Puttonen, P., and Granström, A.: Impact of stand structures on surface fire ignition potential in *Picea abies* and *Pinus sylvestris* forests in southern Finland, Can. J. Forest Res., 35, 410–420, 2005.

Tietäväinen, H., Tuomenvirta, H., and Venäläinen, A.: Annual and seasonal mean temperatures in Finland during the last 160 years based on gridded temperature data, Int. J. Climatol., 30, 2247–2256, 2010.

Tuomenvirta, H.: Reliable estimation of climatic variations in Finland. PhD dissertation. Finnish Meteorological Insitute, Contributions, 43, 158 pp., 2004.

Van Wagner, C. E.: Development and structure of the Canadian Forest Fire Weather Index System, Canadian Forest Service Forestry Technical Report, 35, 36 pp., 1987.

Vajda, A., Mäkelä, H. M., and Venäläinen, A.: Evaluation of two fire danger rating methods in the boreal forest environment (Finland), Boreal Environ. Res., in review, 2012.

Venäläinen, A., and Heikinheimo, M.: The Finnish forest fire index calculation system, in: Early warning systems for natural disaster reduction, edited by: Zschau, J. and Kuppers, A., Springer, Berlin, 645–648, 2003.

Venäläinen, A., Jylhä, K., Kilpeläinen, T., Saku, S., Tuomenvirta, H., Vajda, A., and Ruosteenoja, K.: Reoccurrence of heavy precipitation, dry spells and deep snow cover in Finland based on observations, Boreal Environ. Res., 14, 166–172, 2009.

Vivchar, A.: Wildfires in Russia in 2000–2008: estimates of burnt areas using the satellite MODIS MCD45 data, Remote Sens. Lett., 2, 81–90, 2011.

Wallenius, T.: Menneet metsäpalot Kalevan kankailla, Metsähallituksen luonnonsuojelujulkaisuja, Sarja A, 176, 46 pp, 2008 (Past forest fires in Kalevala National Park and neighbourhood, in Finnish with abstract in English).

Ylhäisi, J. S., Tietäväinen, H., Peltonen-Sainio, P., Venäläinen, A., Eklund, J., Räisänen, J., and Jylhä, K.: Growing season precipitation in Finland under recent and projected climate, Nat. Hazards Earth Syst. Sci., 10, 1563–1574, doi:10.5194/nhess-10-1563-2010, 2010.

Zackrisson, O.: Influence of forest fires on the North Swedish boreal forest, Oikos, 29, 22–32, 1977.