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Evaluation of the Performance of Meteorological Forest Fire Indices for German Federal States

A. Holsten[a], A. R. Dominic[a], L. Costa[a], J. P. Kropp[a]

[a]Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany
Corresponding author: Anne Holsten: Tel.: +49 0 331 288 2689, E-mail address: holsten@pik-potsdam.de

Abstract

Meteorological forest fire risk indices have been developed to forecast the risk of fire occurrence and aid forest managers to take suitable preventive measures. We evaluate five meteorological fire risk indices and relevant meteorological variables for their predictive capacity against monthly fire statistics for 13 German states between 1993 and 2010. Mean relative humidity stands out as the best overall predictor (for 9 out of 13 states) for the recorded number of fires with a median correlation coefficient for Germany of -0.7. The indices with best explanatory power were, in decreasing order, the German modified M-68, the Canadian Fire Weather Index and Angström. The correlations of fire data with relative humidity and fire indices were stronger for states particularly prone to fire occurrence. At the monthly scale, correlations of relative humidity and fire indices with area burnt are in average weaker than with the number of fires. For the same time period, we investigated the performance on a daily scale for the state of Brandenburg. In this case, the performance of fire indices and relative humidity were more similar than at the monthly level. In addition, the number of fires could be explained equally well as the area burnt. Climate projections under different temperature and moisture conditions consistently indicate a monthly decrease in relative humidity until 2060, particularly in the summer months. Future monthly values of M-68 also denote a considerable increase of fire risk in summer. The increase in fire risk at the beginning and end of the fire season points to a possible extension of the current fire season. Our results reveal that mean relative humidity is sufficient to describe observed fire occurrences in Germany at both monthly and daily scales. Correlation coefficients were robust in state, country, monthly and daily analysis. Due to its predictive power and simplicity of calculation, relative humidity is a valid or better alternative in Germany as a proxy for monthly forest fire risk.

Keywords: Fire index, scenario, climate change, Baumgartner, Nesterov

1 Introduction

Forest fires are considered a major disturbance in forest ecosystems. Their occurrence can lead to considerable ecological and economic losses as well as global CO_2 emissions comparable to those from fossil fuel combustion (Bowman et al., 2009). Because of their ability in providing quantitative estimates on the chance of forest fires' occurrence, fire risk indices based on weather data have become important tools in evaluating regional fire risk potential over time. Although the existence of strong correlations between fire occurrence and weather conditions (Viegas et al., 1999; Carvalho et al., 2008; Flannigan et al., 1998) supports the rationale behind using weather-based indices for fire risk forecasting, their ability in describing observed fire patterns has been reported to vary within the respective season. For example, after testing several fire risk indices in the Mediterranean region, Viegas et al. (1999) concluded on the existence of seasonal variability regarding the predictive quality of fire indices; namely between summer-autumn and winter-spring fires. In addition, the explanatory power of fire indices varied considerably at spatial scales below national (Padilla and Vega-García, 2011). The use of fire indices for preventive planning requires therefore a thorough evaluation of their spatial and temporal applicability.

In Germany, two meteorological fire indices have been developed to evaluate fire risk on a daily basis - the M-68 and the Baumgartner Index. The latter was used in former West Germany, while the M-68 was originally developed and applied in former East Germany (Käse, 1969; Flemming, 1994). The M-68, in a modified form, is currently the standard index used by the German Weather Service (DWD) to provide forest fire risk on a daily basis. Both indices have been subject to evaluations of performance on annual (Badeck et al., 2004) and daily levels (Wittich, 1998). However, their comparison was temporally restricted to yearly numbers of forest fires or to a time frame of 1 year, respectively, and geographically limited to one federal state in both studies. It remains an open question to what extent commonly used fire risk indices like the Canadian Fire Weather Index (FWI), a sub system of the Canadian Forest Fire Danger Rating System (CFFDRS), the Angström index or the Nesterov Index provide an alternative, or a complement, to the M-68. With a comprehensive analysis on fire indices' performance at German state level still missing, there is

Table 1: Overview of the states: Number of climate stations used for indices evaluation, mean annual temperature, annual precipitation sum (1993-2010), forest cover in ha (based on the applied database of forest fires), share of forest area compared to the state's area, Total number of fires and area burnt [ha] from 1993-2010. For abbreviations of the states, see Figure 1.

State	# Stations	Tmean [°C]	Prec. [mm]	Forest area [ha]	Forest area [%]	# fires	Area burnt [ha]
BW	130	9.3	986.8	1281409	35.8	479	164.6
BY	384	8.4	988.5	2386027	33.8	1318	1497.5
BB	43	9.4	584	973017	33	7261	4526.8
HE	109	9.4	775	813092	38.5	1074	255.9
MV	54	9.1	633.7	492673	21.2	1232	638.5
NI	141	9.6	817.8	1081248	22.7	1791	710.3
NW	121	9.8	949.7	835763	24.5	858	395.2
RP	75	9.6	774.1	794432	40	980	318.4
SL	8	10	892	92131	35.9	115	82.1
SN	31	8.3	838	471290	25.6	1564	913.6
ST	37	9.2	674.9	454640	22.2	2055	1157.6
SH	31	9.2	811.2	154602	9.8	172	58.3
TH	46	8.5	740.7	490276	30.3	493	138.9

also a lack of information on how much the fire indices better aid predictability compared to using raw weather variables. This is a relevant point to consider since it is known that fire indices are particularly sensitive to input variables such as rainfall, temperature and wind conditions (Dowdy et al., 2010). Finally, while the increase in fire risk at large spatial scales due to climate change has been established (Marlon et al., 2009; Lindner et al., 2010), researchers have been making use of fire risk indices to assess climate change implications in fire regimes at national levels (Carvalho et al., 2011; Giannakopoulos et al., 2009).

In this paper we aim at filling in the existing knowledge gaps on the relations between fire occurrences and climate conditions in Germany by providing a comprehensive comparison of the monthly performance of multiple forest fire indices for 13 states as well as their performance on a daily level for one state. In addition, we test the explanatory power of fire indices against their raw input variables and evaluate if the modified M-68 - commonly applied in Germany - shows the overall best performance. We then analyze the potential future monthly fire regime in Germany under climate change based on the best performing approaches identified.

2 Study area description

In general, Germany is characterized by a temperate climate with maritime components near the North and Baltic Sea and continental influences increasing in southeast direction. Maximum daily temperature ranges between 12.9 °C and 14.1 °C among the states, annual precipitation between 620–1000 mm averaged over Germany during 1993–2010. With an annual sum of about 600 mm during this time period, Brandenburg (BB) is the driest state, while Baden-Württemberg (BW) Bavaria (BY) and North Rhine-Westphalia (NW) are among the wettest with over 1000 mm. Around 31 % of Germany is covered by forests (BMELV, 2005), dominated by Norway spruce, Scots pine, European beech and oak. Historically, the drier and pine-dominated region of the north-eastern German lowlands has been the most fire prone area. Exceptional conditions of high temperatures and low values of precipitation and relative humidity were recorded in the year 2003, together with comparatively high fire activity. Germany comprises 16 Federal states, three of which are city states which account for less than 0.2% of total forest area (Fig. 1). An overview over the characteristics of the considered states regarding climate, forest cover and forest fires is provided in Table 1.

3 Data

We obtained data on the monthly numbers of forest fires and area burnt from annual reports of the German Federal Agency for Agriculture and Food (BLE) for each Federal State. We restricted our analysis to the years 1993-2010, where monthly fire statistics for both public and private owned forests are available. Further, we obtained daily forest fire data for the state of BB from the Federal Forestry Office Brandenburg for the same time period. Climate data from the German Weather Service (DWD) for 1218 operating measurement stations (Fig. 1) was used for the calculation of fire risk indices. This dataset comprises daily values of maximum, mean and minimum temperature, total precipitation, and means of relative humidity, air pressure, water vapor pressure, sunshine hours, cloudiness, radiation and wind velocity. Additionally, noon relative humidity was calculated based the long-term climate data of the Potsdam weather station, BB, between 1893–2010.

For future projections of fire risk, we use the climate data from the STAtistical Resampling Scheme (STARS, version II) (Werner and Gerstengarbe, 1997; Orlowsky et al., 2008), with a simulation period from 2007 to 2060. For this simulation, observed climate data is resampled using a cluster analysis, whereby different temperature trends from 0 to 3.0 K increasing in steps of 0.5 K are imposed (Werner, 2011). We evaluate future fire risk for a 1 K, 2 K and 3 K temperature rise under medium humidity conditions. Complementarily, for the 2 K rise scenario, we analyze future fire risk under rela-

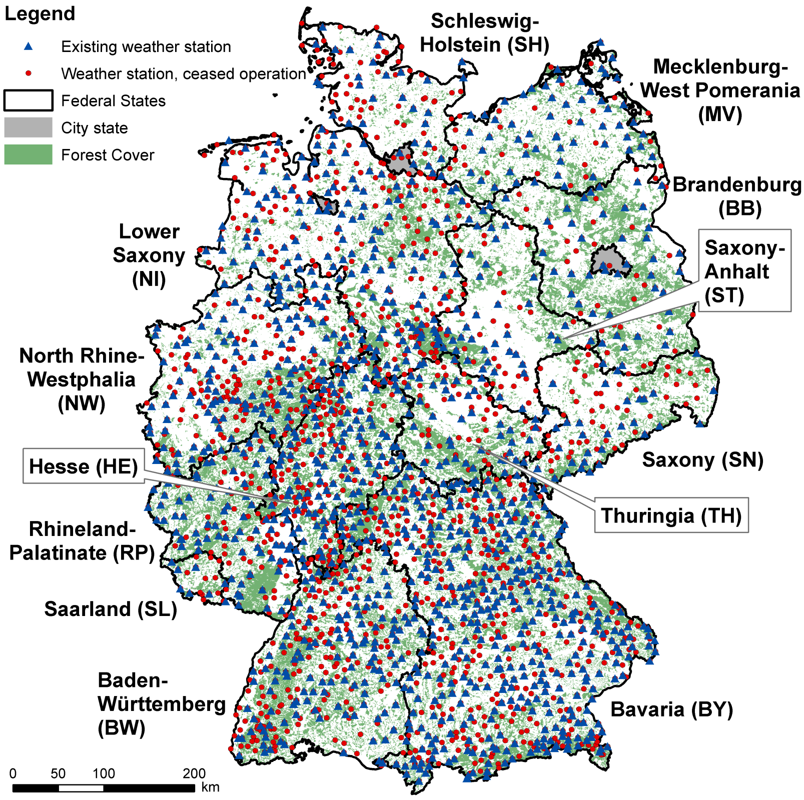

Figure 1: Location of weather stations and forested area within the German federal states. Only non-city states were analysed. Note that abbreviations referring to the federal states are introduced.

tively dry and wet conditions. All the temperature scenarios are in principle equally probable as they depend on future global demographic trends and greenhouse gas emission rates that cannot be exactly anticipated. The different humidity conditions are generated from different runs of this stochastic model. Model data before 2007 represents the observed climate data from DWD for a larger set of climate stations (2337), as more stations were in operation until then (see Fig. 1). Missing climate data was spatially and temporally interpolated by the Inverse-Distance Method (taking a maximum of 5 surrounding stations into account) and for temperature and air pressure, a correction based on elevation was applied. This is due to the larger spatial coverage of precipitation measurements than e.g. temperature measurements. This interpolation was applied to the dataset of observed climate, on which the simulation of climate for the projection period is then based. To compare past and future climate and fire regime conditions, we use data of the STARS model for the time frames 1961-1990 (observed) and 2031-2060 (simulated).
Finally, we weighted the fire risk indices for each station by the proportional area of the surrounding forest cover to reduce the bias from inhomogeneous distribution of forests. Forest cover for Germany was obtained from the CORINE Land Cover vector data (CLC2006) (EEA, 2009) by aggregating the broad-leaved (class 311), needle-leaved (class 312) and mixed (class 313) forest classes.

4 Methods

We calculate five meteorological fire risk indices and test their ability to reproduce the monthly pattern of forest fire statistics in German federal states. Station based daily fire indices were calculated and spatially and temporally aggregated for analysis with the monthly fire statistics. A summary of the investigated risk indices, the required and applied input variables and meteorological variables used is provided in Tab. 2.

Two of these approaches were developed specifically for Germany—the Baumgartner Index and the M-68. The former was developed for the state of BY and is based on precipitation and potential evapotranspiration of the previous five days (Baumgartner et al., 1967). Due to a lack of data, we calculated evapotranspiration with temperature, radiation and relative humidity according to the Turc/Ivanov method (Turc, 1961; Wendling and Schellin, 1986) (see also equation in the supplementary material). The M-68 is based on a formerly used index for East Germany (Käse, 1969; Flemming, 1994). Since the German unification the M-68 has been modified and is currently used as the standard index to provide forest fire risk on a daily basis by the German Weather Service (Friesland and Löpmeier, 2007). Additionally to weather data, the modified M-68 also requires phenological data, namely, the onset day of the bud burst of birch (*Betula pendula*) and robinia (*Robinia pseudoacacia*). Burst dates were

Table 2: Overview of the considered forest fire indices and their input meteorological variables on a daily basis (Tmean=mean temperature, Tmax=maximum temperature, RH=relative humidity, RHnoon=noon relative humidity, RHadj= RH adjusted to represent noon relative humidity, P=precipitation, W=wind velocity, EP=potential evapotranspiration, R=radiation, SD=saturation deficit, DPT=dew point temperature, AP=air pressure)

Index	**Source**	**Original input**	**Applied input**
Baumgartner (Ba.)	Baumgartner et al. (1967)	P, EP	P, Tmean, R and RH
Modified M-68 (M-68)	Käse (1969); Flemming (1994), modified to account for wind and fire prone regions (Landesforst Mecklenburg-Vorpommern, 1999)	P, Tmax, W, SD, phenology (bud burst dates of black locust and birch)	P, Tmax, W, RHadj, Tmean
Canadian Fire Weather Index (FWI)	Van Wagner and Pickett (1985); Van Wagner (1987), classification after (Camia and Amatulli, 2010)	P, W, RHnoon	P, W, RHadj
Angström (Ang.)	Å ngström (1942), applied in Skvarenina et al. (2004)	Tmax and RHnoon	Tmax, RHadj
Nesterov (Ne.)	Nesterov (1949), applied in Skvarenina et al. (2004)	Tmax, P, DPT	Tmax, Tmean, RH and AP

calculated employing temperature sum models for birch (Schaber, 2002, p. 145) and robinia (Chmielewski et al., 2004, p. 75). Due to a lack of data, we substituted days with snow cover by snow days, defined as days with minimum temperature below 0 °C and precipitation above 0 mm. Thereby we underestimate the fire risk, however, this is expected to be a minor influence during the fire season. Based on applications of this index by Suckow et al. (2005); Badeck et al. (2004), we calculate the required saturated vapor pressure by using the daily maximum temperature according to Bolton (1980). As modifications of the index consider the fire proneness of the region (Landesforst Mecklenburg-Vorpommern, 1999), we classified BB as the highest fire prone state, Saxony (SN), Mecklenburg-West Pomerania (MV), Saxony-Anhalt (ST) and Lower Saxony (NI) as medium and the rest of the states with the lowest value, based on Wittich (2011). The Canadian FWI is currently used to forecast fire risk for whole of Europe by the European Forest Fire Information System (EFFIS) and its application to the global scale is also planned (Dimitrakopoulos et al., 2010). This complex index comprises six components providing probabilities of fire ignition and fire behavior, and takes into account the effect of fuel moisture. The Angström index is based on atmospheric dryness of the same day (Å ngström, 1942) and has been tested for other regions in Europe with satisfactory results (Skvarenina et al., 2004; Ganatsas et al., 2011; Reineking et al., 2010). Finally, the Nesterov Index was developed for use in Russia (Nesterov, 1949; Groisman et al., 2007). It has been used as a basis for the development of the German M-68 Index. The required dew point temperature was estimated via the relation between temperature, relative humidity and air pressure based on Martinez (1994). Except Angström, all indices are cumulative indices, in that fire risk of a particular day is also dependent on the weather conditions of the previous days. The M68, FWI and the Angström require noon relative humidity as an input. However, only data on mean daily relative humidity was consistently available for all climate stations. Where noon relative humidity was required, we adjusted the mean values of relative humidity according to the monthly differences observed between mean and minimum relative humidity for the long-term station of Potsdam. The differences ranged between 12 and 16 % between March and October of 1893–2010.

Absolute values of fire risk indices are often grouped into fire danger classes that provide a qualitative description of the risk for ease of applicability. We adopt the common danger classes, ranging from 5 (high) to 1 (low) and convert daily index values at state level into danger class according to the description of the respective indices. We apply the classification of the FWI as currently adopted to European conditions (Camia and Amatulli, 2010). The Angström index is classified according to Skvarenina et al. (2004). Note that the Baumgartner Index considers a classification dependent on the respective month (Baumgartner et al., 1967) and the danger classes of the modified M68 are dependent on the state and wind velocity (Landesforst Mecklenburg-Vorpommern, 1999).

Although fire index values could be calculated on a daily basis, fire statistics were only available at monthly level for each state. In order to compare index values from climate stations with monthly fire statistics of German states, we therefore aggregate fire index values spatially (state level) and temporally (monthly level). Because the reported number refers to fires that occur in forested areas, index values from stations with small forest area in their vicinity should in principle have a lower weight on the final fire index value when compared to those close to large forests. We therefore weighted the classified index value of each station by the share of forest within its surroundings (delineated by Thiessen polygons) before spatially averaging fire index values of stations over the respective state. Thus, each stations daily index value (from 1 to 5) is averaged over all the stations within a state to generate a single daily value for the whole state (classes as decimal number). The analysis has been carried out based on the index classes since the classification is inheritably included in the methods of some indices, e.g. the Baumgartner index applies month-specific classifications and the modified M-68 depends on wind velocity and geographic region for the classification. Further, the indices involve unequally spaced classes, according to their developed algorithms. To be able to compare the performance of all selected indices, we therefore focus their classified values. However, in order to test for possible losses of explanatory power due to the classification of index values into fire danger classes, we also correlated unclassified maximum and mean values of the Angström, FWI and Nesterov index with fire statistics. In these indices danger class classification is not an integral part of their calculation.

Regarding the temporal aggregation to the respective months, we calculated the monthly mean fire danger class as the monthly average of the above described classified index values for the specific state. Additionally we counted the number of days falling into different class combinations (i.e. days with danger class 5, days with danger classes 4 to 5, days with danger classes 3 to 5 and days with danger classes 2 to 5). We then correlated the index values (classified monthly mean and counts of danger classes) with observed monthly number of fires and area burnt for every state investigated.

In order to check the performance of raw weather variables, mean values of daily maximum and mean temperature, relative humidity and daily sum of precipitation were also considered in the correlations. These variables are the key inputs in most of the indices applied (Tab. 2) and are also considered in similar studies which analyze weather conditions during high fire seasons (Carvalho et al., 2010; Ganatsas et al., 2011; Skvarenina et al., 2004). They were weighted by the surrounding forest area analogously to the approach for the index values.

For the monthly analysis a total of 144 data points (18 years with 8 months each) were available for the correlation analysis (the applied data can be obtained from the authors on request). We restricted our analysis to the 13 non-city states (Fig.1) due to low shares of forest area in Berlin, Bremen and Hamburg. In addition to the monthly analysis, we have also tested the performance of the fire indices and meteorological variables against daily forest fire statistics for Brandenburg between 1993-2010. All fire indices and correlation coefficient (ρ) values were obtained using programming language R (R Development Core Team, 2009). Spatial data was processed with ArcGIS 9.2, ESRI.
We chose Spearman's ranked correlation test to evaluate the predictive power of both fire indices and raw input variables. This was determined by the fact that danger classes are ordinal, i.e. they are derived from unequal intervals (or ranges) of unclassified values and as such cannot be treated as continuous variables.

5 Results

Overall, correlation between the meteorological variables or fire indices and the number of fires is higher than for area burnt (Tab. 3 and Table A1 in supplementary material). For further analysis we concentrate on the correlation values obtained for the number of fires.

At the national level, relative humidity yields the highest median correlation coefficient value, respectively -0.7 (Fig. 2 and Tab. 3). Other meteorological variables considered show very low correlation values for number of fires, in general below 0.58 (obtained for maximum temperature). Among the different meteorological indices, the best combination of danger classes returned similar correlations as the mean for the indices M-68 (0.64 and 0.63), FWI (0.6 and 0.63) and Angström (0.61 and 0.62). Overall weaker correlations were found for the Baumgartner (0.59) and Nesterov (0.52) indices.

While the Angström, Nesterov and FWI indices achieve the best overall median performance when mean index values are considered, Baumgartner and M-68 Indices better explain observed fire patterns when danger classes 2 to 5 are used as an independent variables. We further investigate whether using the number of days below a certain threshold of relative humidity would improve the correlation with the number of fires. If monthly number of days with relative humidity below 70 % is used as independent variable, a maximum correlation coefficient of -0.72 is obtained (see Fig. A1 in supplementary material), which is only slightly higher as when mean monthly relative humidity is considered. We also tested the performance of the monthly minimum of relative humidity as a proxy for forest fire occurrence, however this leads to a lower correlation value of 0.69 (median of all states). Similarly, monthly maximum and mean values of unclassified indices (Angström, FWI and Nesterov) did not improve the correlation coefficient compared to the mean of classified values. We therefore focus on analyzing mean values of relative humidity and mean classified index values.

At state level, we find that correlation values can be highly diverging (Tab. 3). Regarding average relative humidity, correlation values for German states range between -0.39 for Saarland (SL) and -0.91 for BB. In fact, relative humidity alone was found to be the best proxy for the occurrence of forest fires in 9 of the 13 investigated states. Correlations were found to be stronger (above 80%) in typical fire prone states regarding the number of fires, namely: BB, SN, MV and ST, in de-

Table 3: Spearman's correlation coefficients (ρ) between monthly number of fires and meteorological variables as well as fire danger indices for 13 German Federal States from 1993 to 2010. Average classified index values are considered as well as number of days per month falling into different categories of danger classes. ρ values were significant at the 95% confidence level except for those in italics. The best performing approach (for ρ ¿ 0.5) for each state is marked in bold and underline, the second best in bold. The numbers in brackets after the fire index abbreviation represent the range of danger classes included to perform the fit. NAs signify zero days with that danger class for the whole state.

	BW	BY	BB	HE	MV	NI	NW	RP	SL	SN	ST	SH	TH	Median
Tmax	0.2	0.3	0.59	0.31	0.42	0.44	0.28	0.48	*0.02*	0.52	0.51	0.35	0.47	0.42
Tmean	*0.16*	0.26	0.53	0.27	0.36	0.39	0.24	0.45	*-0.02*	0.48	0.46	0.33	0.42	0.36
P	-0.3	-0.19	-0.21	-0.31	-0.29	-0.37	-0.28	-0.27	-0.2	-0.29	-0.23	-0.25	-0.33	-0.28
RH	-0.48	**-0.74**	**-0.9**	**-0.7**	**-0.82**	**-0.75**	**-0.7**	-0.58	-0.39	**-0.86**	**-0.8**	-0.44	**-0.69**	**-0.7**
Ang.(5)	0.29	0.36	0.78	0.5	0.55	0.55	0.51	0.49	0.19	0.61	0.68	0.46	0.55	0.51
Ang.(4-5)	0.36	0.55	0.84	0.57	0.67	0.59	0.55	0.55	0.21	0.71	0.73	0.43	0.63	0.57
Ang.(3-5)	0.39	0.61	0.83	0.58	0.72	0.68	0.57	**0.6**	0.23	0.78	0.74	**0.5**	0.66	0.61
Ang.(2-5)	0.37	0.52	0.76	0.48	0.63	0.65	0.48	0.57	0.17	0.72	0.67	0.4	0.58	0.57
Ang. (av.)	0.4	0.58	0.83	0.57	0.69	0.69	0.55	**0.62**	0.23	0.77	0.73	0.45	0.65	0.62
Ba.(5)	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	NA
Ba.(4-5)	*0.15*	0.29	0.38	0.26	0.28	0.27	0.24	0.19	0.22	0.42	0.29	*0.01*	0.28	0.27
Ba.(3-5)	0.34	0.52	0.62	0.56	0.6	0.41	0.48	0.32	0.48	0.58	0.52	0.25	0.42	0.48
Ba.(2-5)	0.46	0.64	0.64	0.59	0.59	0.59	0.57	0.45	0.42	0.65	0.6	0.33	0.43	0.59
Ba. (av.)	0.44	0.65	0.67	0.62	0.62	0.57	0.57	0.42	0.46	0.67	0.63	0.32	0.46	0.57
Ne.(5)	0.18	0.2	0.36	0.24	0.17	*0.1*	*0.13*	*0.16*	0.21	*0.12*	0.26	*0.08*	*0.15*	0.17
Ne.(4-5)	0.37	0.41	0.69	0.49	0.48	0.48	0.39	0.51	0.24	0.56	0.62	0.36	0.55	0.48
Ne.(3-5)	0.38	0.4	0.64	0.5	0.6	0.58	0.4	0.48	0.28	0.63	0.59	0.43	0.64	0.5
Ne.(2-5)	0.34	0.35	0.53	0.41	0.52	0.54	0.37	0.47	0.25	0.61	0.49	0.34	0.51	0.47
Ne. (av.)	0.38	0.42	0.67	0.51	0.61	0.61	0.41	0.52	0.29	0.67	0.62	0.41	0.65	0.52
M-68 (5)	*NA*	*NA*	0.54	*NA*	*NA*	*NA*	*NA*	*NA*	*0.16*	*NA*	*NA*	*NA*	*NA*	0.35
M-68(4-5)	0.37	0.38	0.62	0.34	0.46	0.35	0.24	0.25	0.4	0.43	0.47	*0.14*	0.3	0.37
M-68(3-5)	0.33	0.51	0.73	0.5	0.64	0.52	0.39	0.33	0.41	0.65	0.65	0.3	0.44	0.5
M-68(2-5)	0.48	0.68	0.78	0.68	**0.75**	0.64	**0.63**	0.53	0.5	0.76	0.71	0.37	0.62	**0.64**
M-68 (av.)	0.49	**0.69**	0.81	**0.7**	0.75	0.63	**0.63**	0.53	0.5	0.77	0.73	0.36	0.63	0.63
FWI (5)	*0.15*	*NA*	*0.13*	*NA*	*NA*	*NA*	*NA*	*NA*	0.24	*0.14*	*0.14*	*NA*	*0.15*	0.15
FWI (4-5)	0.4	0.32	0.71	0.51	0.48	0.38	0.33	0.5	0.28	0.53	0.64	0.49	0.46	0.48
FWI (3-5)	0.44	0.59	**0.86**	0.6	0.74	0.65	0.52	0.59	0.25	**0.79**	**0.76**	**0.52**	**0.63**	0.6
FWI (2-5)	0.44	0.6	0.77	0.59	0.71	0.69	0.54	**0.6**	0.26	0.75	0.7	0.47	0.68	0.6
FWI (av.)	0.45	0.61	0.83	0.63	0.73	**0.7**	0.55	**0.62**	0.28	0.78	0.74	0.5	0.7	0.63

creasing order of correlation value. We found very low correlation values for the state of SL, which has, in absolute terms, the lowest number of fires per year in Germany. Finally, correlation coefficients for relative humidity at state level are statistically different from the others at the 95% confidence level using the paired Wilcoxon T test. The monthly correlation between the meteorological variables and the forest fire indices with monthly number of fires for each state are significant in more than 90% of the cases.

The monthly distribution of number of fires, mean relative humidity and the best predictive fire index is shown in Fig. 3. Results refer to three federal states that historically present high number of fire occurrences, namely, BB, SN and ST. Regarding the number of fires, all three states show a sharp increase from March to April. Between April and August the level remains relatively constant in some cases with a slight increase in late summer such as in ST. From August to September a sharp decrease in average fire numbers is observed, denoting the end of the fire season. Mean relative humidity captures fairly well the above described yearly pattern of fire occurrences. The slight spring drop in relative humidity matches the increase in fire observations for all considered states and the mean relative humidity values remain rather constant until August, in line with the period when high fire activity is registered. By comparison, the pattern of fire risk obtained with the FWI (classes 3 to 5) rise sharply until May for BB and SN. In ST, FWI values increase monotonically until July and August, missing the sharp spring increase in fires.

The overall ability of mean relative humidity in describing monthly fire numbers raises the logical question whether the same holds in case of daily fire occurrences. In order to investigate such possibility, we have analyzed daily correlation values between the investigated set of independent variables and forest fire statistics for BB for the period 1993–2010. Correlations between daily meteorological variables and fire index class are now on par with those for area burnt (Tab. 4). This is in contrast to what was observed at the monthly level. The mean daily relative humidity (ρ =-0.62), together with the FWI and Angström (both ρ =0.63) indices provide the highest correlation values. Note that due to the differing aggregation level of monthly and daily analysis the absolute value of the correlation coefficients are not directly comparable. In a statistical sense, there is no difference between using relative humidity or the previous highlighted fire indices at monthly or daily scales in BB.

To test the robustness of the results based on the Spearman's ranked correlation test, we have additionally analysed the daily fire performance of Brandenburg with the ranked percentile curve (after Eastaugh et al., 2012) and the ROC curve (Receiver Operation Characteristic). For this, the data on daily fire occurrence was converted to a binary data set of presence and absence of forest fires. Again, relative humidity performs similarly well as other indices such as the

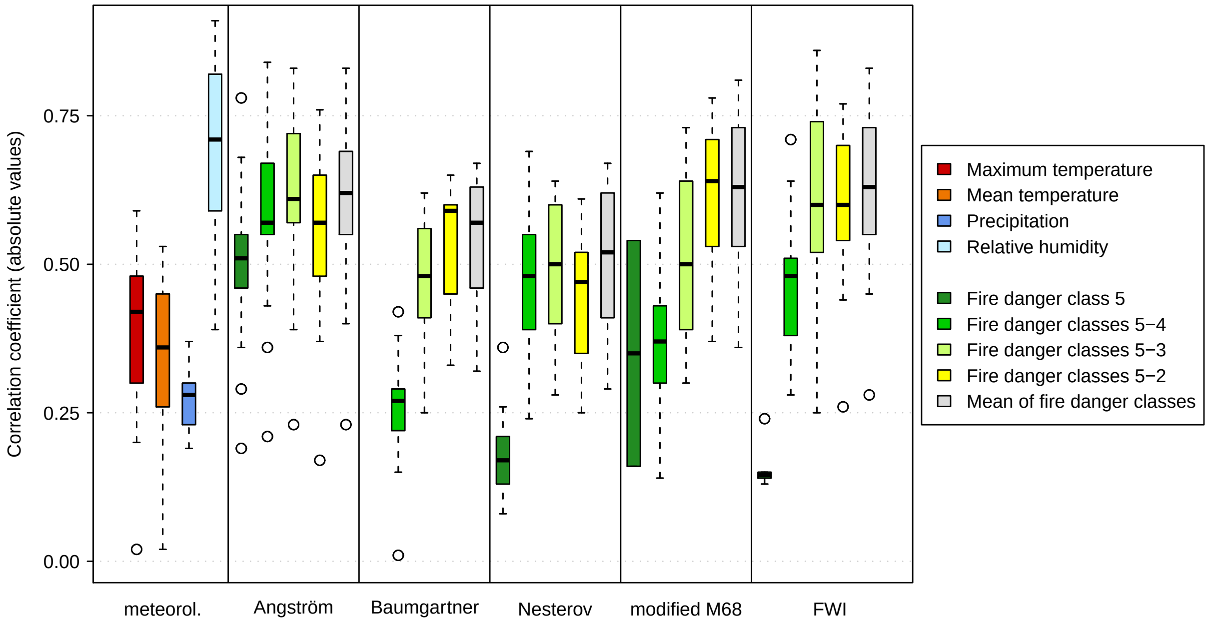

Figure 2: Boxplot of Spearman's correlation coefficients (ρ) (absolute values of coefficients) between monthly number of fires and meteorological variables as well as fire danger indices for 13 German Federal States from 1993 to 2010. In total, correlation values for meteorological variables and five investigated indices are shown. For each fire index we display the correlation ranges obtained with the mean monthly values and the different combinations of danger classes. In each box the horizontal line represents the median, the outer box the 25th and 75th percentiles, the whiskers either the maximum or 1.5 times the inter-quartile range. Outliers are marked by circles. The sequence of the boxes follows the same order as the legend description.

FWI or the Angström index (for more information see supplementary material).

Table 4: Correlation coefficients of daily meteorological variables and index classes with daily number of forest fires and area burnt for the state BB. The fire data was directly correlated with the respective fire danger class. ρ values were significant at 95% confidence level. The best performing approach for each state is marked in bold and underline, the second best in bold.

	number of fires	area burnt
Tmax	0.49	0.47
Tmean	0.44	0.41
P	-0.28	-0.28
RH	**-0.62**	**-0.62**
Angström	0.63	**0.61**
Baumgartner	0.53	0.52
Nesterov	0.53	0.51
M-68	0.61	0.59
FWI	**0.63**	**0.61**

We further investigated future forest fire risk based on the identified two best performing approaches. In Fig. 4 we therefore show the possible future shifts in fire risk according the proxies "mean relative humidity" (panels a and c) and "number of days with danger classes 2 to 5" given by the M-68 index (panels b and d). The projections show a consistent increase in risk for relative humidity independent of the considered scenario. The scenarios influence nevertheless the magnitude of changes (deviation from historical values). When all scenarios are considered, on average relative humidity will reduce by 1.2-3 % points in spring. In summer months, reductions between 2 and 4.8 % points are estimated (Fig. 4c). If the M-68 is used as proxy we obtain heterogeneous patterns of fire risk. For example, in the months of May we see a lowering in fire index values under all scenarios considered. For the remaining months of the year changes in fire index values are positive with a maximum deviation in July (an increase of 2 to 9.2 days belonging to danger classes 2 to 5). Independent of the scenario and proxy, the spring fire risk does not show a substantial deviation from historical values (see Fig. 4 c and d). Overall, the highest spring fire risk is attained under a 2 K temperature increase and dry conditions, whereas a 3 K rise under medium moisture conditions leads to a stronger increase in summer fire risk. Further, the projections point to higher fire risk in March and October, particularly according to relative humidity, thus prolonging the potential fire season.

6 Discussion

We evaluated five meteorological forest fire indices and four meteorological variables regarding their predictive performance for Germany at state-level on a monthly basis. We also tested their performance on a daily

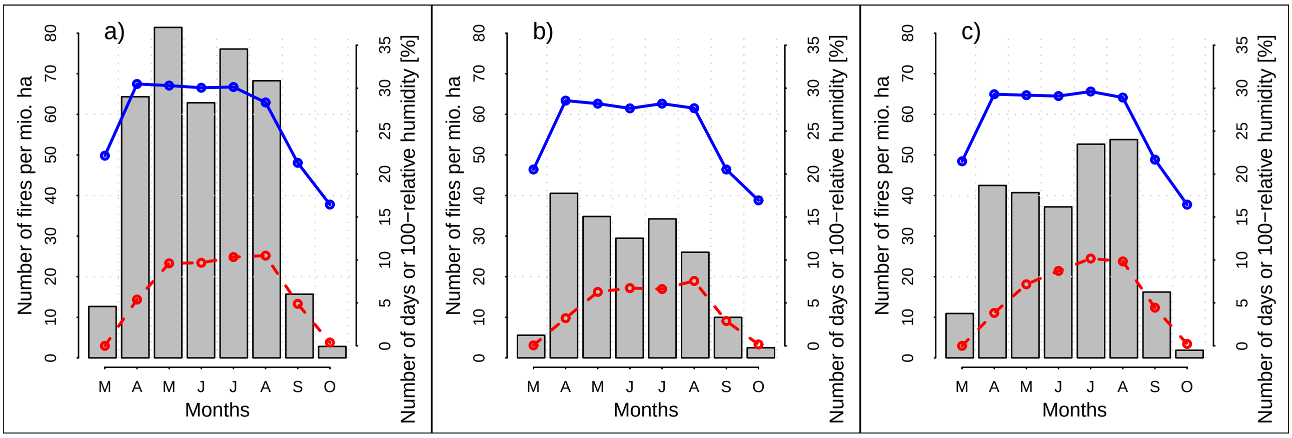

Figure 3: Observed monthly number of forest fires (grey bars), relative humidity values (blue continuous line) and number of days falling falling into the index classes 3-5 for the FWI (red dashed line) for the three most fire prone states a) BB, b) SN and c) ST. The right y-axis represents both the frequency of danger classes (days) and the relative humidity. Note that for better comparability with the indices and the observed fires, relative humidity values are reversely displayed, as the difference to 100%.

basis for the state of BB. These indices have not been compared for Germany on a monthly scale before. Also, there was a lack of a comprehensive comparison of their performance against meteorological input variables. However, such an analysis is essential to justify the application of these indices some of which are quite complex comprising many parameters.

Relative humidity demonstrates a predictive power comparable to the investigated indices in the daily analysis and a superior power for most of the states in the monthly analysis. It is plausible that relative humidity in itself is a good indicator of fire conditions and occurrence – in accordance with Wittich (1998) and Skvarenina et al. (2004) – as it indirectly includes information concerning temperature, precipitation and biophysical processes of the surroundings . We have identified a lack of substantial improvement in the explanatory power of the fire indices when compared to the capacity of relative humidity alone in describing observed fire patterns. This was true both at monthly and daily time scales in Germany and BB respectively.

The fact that fire indices do not stand out regarding their explanatory power during the monthly analysis is intriguing. This is surprising, since the indices here evaluated incorporate relative humidity either directly in their equations (eg. Angström Index) or indirectly in order to derive auxiliary parameters (e.g., dew point temperature calculation in the Nesterov index). On a daily basis, the performance of fire indices FWI, M-68 and Angström are on par with the results obtained with relative humidity (see Tab. 4). Among the indices, the modified M-68 used by the German Weather Service showed the best overall performance at a monthly scale. This is in line with results for the severe forest fire year of 1975, where the M-68 Index provided better results than the Baumgartner Index, regarding the reproduction of the observed daily pattern of burnt area (Wittich, 1998). However, we found that the FWI adapted to European conditions constitutes a valid alternative to the M-68 in the most fire prone states. At daily scales for the state of Brandenburg, it seems that relative humidity, the FWI, the modified M-68 or the Angström index are equally valid descriptors. The potential of relative humidity to outperform established forest fire indices has already been documented. For example, Padilla and Vega-García (2011) shows a substantial heterogeneity of independent variables in explaining fire statistics across 53 eco-regions in Spain: minimum relative humidity outperformed FWI - as well as several fuel moisture models - as the main explanatory variable of a logistic regression for large regions of the country. Skvarenina et al. (2004) also stresses the sensitivity of fires to relative humidity for Slovenia. The importance of relative humidity has been previously highlighted also for Germany (Wittich, 1998). For example, during the extreme years of 1992 and 1993 most fire occurrences have been recorded in days with relative humidity ranging from 40 to 15% (Lange, 1994). Hence, our results reinforce the spatial heterogeneity of fire predictors and the important role of relative humidity.

Our approach has some limitations. Not all input variables required in fire indices calculation were directly available and have been approximated by means of other meteorological variables (e.g. mean relative humidity correction to minimum relative humidity) or empirical models (e.g. phenology dates). Nevertheless the effect of some approximations (e.g. snow days) can be considered as minor during the fire season. Even assuming that correlation values obtained with fire indices improve when original input data rather that our approximations is used (see Tab. 2), it remains questionable to what extent they would substantially improve beyond the values obtained with relative humidity alone, e.g., -0.91 (BB), -0.87 (SN), -0.83 (MV)

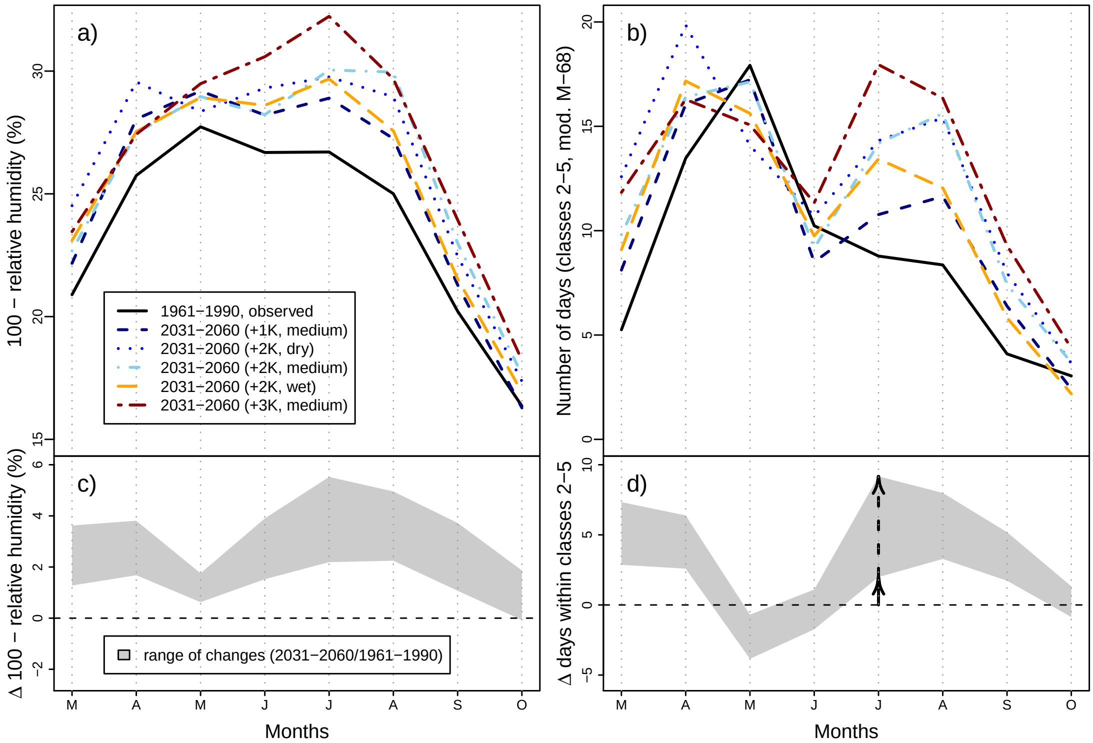

Figure 4: Observed values of relative humidity (left panels) and the modified M-68 index (right panels) averaged over all states between 1961-1990 (black solid line) and projected values of the model STAR for different temperature and moisture scenarios (dashed colored lines). Note that for better comparability with the indices and the observed fires, relative humidity values are reversely displayed, as the difference to 100 %. For the modified M-68 index, all days falling into classes 2-5 were considered. Panels c and d display the difference between the observed monthly values regarding lowest and highest changes as projected according to the different scenarios. For example according to the modified M-68 model, days of fire risk will increase by 2 (moderate scenario) to 9.2 days (extreme scenario) in July (see black arrow in panel d). Inserted legends on the left panels refer equally to the panels on the right.

and -0.81 (ST). Similar to what has been observed at European level (JRC-IES, 2006), we cannot exclude the effect of differences in fire reporting between German states, especially in regions where forest fires are rare, for example SL. Further research could investigate in more detail the influence of the classification scheme of the index values on the performance results, which we have analyzed for three of the five selected indices. Finally, we neglected feedbacks between biosphere and atmospheric conditions for the projection of fire risk. The patterns of vegetation are relevant and have been found to influence the occurrence of future fires. Thonicke and Cramer (2006) used the Regional FIRe Model (Reg-FIRM) embedded in a global vegetation model to study long-term trends in vegetation dynamics and forest fires for BB. They expect that fire risk could be contained within historical levels if the proportion of needle-leaved forests is reduced to at least 50%.

The results from our projections show a considerable increase in summer fire risk, especially when M-68 index is used a proxy for fire occurrence. Spring fire risk also increases but by a smaller amount across all considered scenarios. An increase in summer fire risk is also noted by Camia (2008) in a similar projection of forest fire risk using FWI run on the HIRHAM index for Europe. Their projections for the years 2071–2100 confirm a higher increase for June, July and August than for March, April and May for the IPCC SRES high emissions A2 climate change scenario.

Finally, the ability of relative humidity to describe current monthly patterns of forest fires raises the question to what extent projections of future fire risk for Germany should be based solely on existing indices.

7 Conclusion

In Germany, monthly occurrence of forest fires was found to be conveniently described by variations of relative humidity alone. This was consistent for most of the German states investigated. Commonly used fire indices (including two specifically tailored for Germany) did not improve the explanatory power for number of fires or area burnt obtained with relative humidity alone. This raises the question on the suitability of more complex indices – which often include this meteorologic variable in their formulation – for Germany. When investigating fire occurrences on a daily basis for BB, the performance of relative humidity was comparable to the FWI or the modified M-68. We assume that the good performance of relative humidity is due to its integrative nature, which is related to the atmospheric moisture content that in turn is known to influence the moisture level of surface litter.

Historically, two distinct fire periods were characteristic for Germany, in spring and in summer with medium risk period in June. Projections suggest a strong increase in the summer fire risk and a possible extension of the fire period to February and November, which are presently not considered months of high fire risk. This also means that the indices which are based on certain dates regarding the vegetation period, may need to be tested and optimized for potentially different climatic conditions in future. Other indices, such as the Baumgartner, appear to be not suitable under changing climatic conditions, since fire risk classes are based on fixed monthly corrections.

The apparent robustness of relative humidity in describing past fire events in Germany supports the idea that even simpler predictive models with lower degrees of freedom are possible. This is especially relevant for regions with limited availability of climatic data. Thus, following the principle of Occam's razor, the simpler method is more favorable in this context. This also enhances the application of forest fire warning systems in the practical field and in modeling approaches. However, more research is necessary to investigate these relationships for other regions and different spatial and temporal scales.

8 Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2012.08.035.

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