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Discussions

Temporal variations and change of forest fire danger in Europe in 1960–2012

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Abstract

Understanding how fire-weather danger indices changed in the past, and detecting how changes affected forest fire activity is important in changing climate. We used the Canadian Fire Weather Index (FWI), calculated from two reanalysis datasets, ERA 40 and ERA Interim, to examine the temporal variation of forest fire danger in Europe in 1960–2012. Additionally, we used national forest-fires statistical data from Greece and Spain to relate fire danger and fire activity. There is no obvious trend in fire danger for the time period covered by ERA 40 (1960–1999) whereas for the period 1980–2012 covered by ERA Interim, the mean FWI and the number of high fire risk days shows an increasing trend which is significant at the 99 % confidence level for South and East Europe. The cross-correlation calculated at national level in Greece and Spain between mean yearly area burned and mean FWI of the current season is of the order 0.5–0.6, and demonstrates the importance of the fire-season weather on forest fires. Our results show that, fire risk is multifaceted, and factors like changes in fire fighting capacity, ignition patterns, or landscapes might have played a role in forest fires trends. However, weather trends remain as important determinants of forest fires.

1 Introduction

During the last century, global temperatures in the world increased by about 0.7 °C (IPCC, 2007). However, this change in surface temperature has not been uniform across the whole globe. In Europe the decadal mean surface temperature has risen by about 1.3 °C from pre-industrial times until 2002–2011 (Haylock et al., 2008; EEA, 2012). During the recent 50 yr, warming has been most pronounced in the Iberian Peninsula, central and north-eastern Europe, and mountainous regions; for the Iberian Peninsula, this warming has been most evident in summer (Haylock et al., 2008; EEA, 2012). In addition, warm extremes have become more frequent and cold extremes more rare. As an example, Della-Marta et al. (2007) show that, in Western Europe,

NHESSD
1, 6291–6326, 2013

the average length of summer heat waves are now twice as long as in 1880, and are accompanied by a tripling in the occurrence of hot days. Precipitation changes are not uniform across Europe; while increases in this have been observed in the north (Scandinavia and the Baltic States) a decrease is apparent in some southern areas, like in the Iberian Peninsula and especially in north-western Spain and northern Portugal (EEA, 2012).

These observed changes in climate have the potential to affect fire weather danger parameters and, ultimately, forest fire activity. This poses the question: did fire-weather danger changed in Europe during the last decades? Fire weather danger indices are used to assess fire potential. These combine several relevant climatic/weather variables into suitable indices that forest fires services use to organize their response to forecasted risks. Fire danger indices allow comparisons between both fire season severity and across fire regions, and have been used to project future changes in fire potential due to global warming (e.g. Stocks et al., 1998; Brown et al., 2004; Moriondo et al., 2006; Lehtonen et al., 2013). These indices also enable the examination of past changes in fire danger. The Canadian Fire Weather Index, FWI, based on the Canadian Forest Fire Danger Rating System (Van Wagner, 1987), is one of the most widely-used indices, in use in countries across North and South America, Europe and Asia.

The past variation of the potential fire danger in Europe has been explored in a number of studies. Camia et al. (2008) examined past changes in forest fire danger in Europe using the ERA Interim dataset (Dee at al., 2011) and the Seasonal Severity Rating index based on FWI. According to their analyses, from 1981 to 2010 and onwards, there have been statistically highly significant increases in fire danger in South-Eastern Europe and the southern-most regions of the Iberian Peninsula. Mäkelä et al. (2012) used the fire danger index operational in Finland to estimate the long-term 1908–2011 temporal variation of fire danger in Finland. They found out that the year-to-year variation in fire danger was large, but no significant trend could be detected. Wastl et al. (2012) examined the long term trends in meteorological forest fire danger in the Alps during the period 1951–2010 using several fire danger rating indices, and

NHESSD
1, 6291–6326, 2013

found significant increases in the Western and Southern Alps. The increase was quite small in the Northern Alps and no clear signal could be observed in the inner Alpine valleys.

Koutsias et al. (2013) examined trends in air temperature and their relationship to forest fires in Greece during the years 1894–2010 finding that both increased through time, particularly during the last 40 yr. The annual number of fires and area burnt was strongly correlated with the maximum temperatures and summer heat waves. Additionally, Dimitrakapoulos et al. (2011a) found that there was a positive correlation between the annual droughts and fire occurrence in Greece during the years 1961–1997, which was accompanied with an increasing trend in fire occurrence. Bedia et al. (2012) tested different model reanalysis datasets in the calculation of fire danger for the Iberian Peninsula and found that, for most parts of Spain, the summer season fire danger has increased. They also noted that the results based on the ERA Interim dataset (Dee et al., 2011) were more robust than the results based on the NCEP dataset (Kistler et al., 2001).

In Canada, Gillet et al. (2004) examined the dependence of the area burned by forest fires and temperatures for the period 1920–1999. They observed a pronounced upward trend in area burned by wildland fires in Canada during 1970–1999. During the same decade, Canada experienced a warming during the fire season, and variations in temperature were found to explain much of the variability in area burned. There are also studies displaying the opposite results in regards of occurrence of fires, at least to some extent. For example, according to Turco et al. (2013a, b) both the number of fires and burned area has decreased in Catalonia in Spain 1970–2010 even though the climate has become warmer. Elsewhere in Europe, Wallenius (2011) examined the reason for a major decline in fires in Fennoscandia. His results indicate that the introduction of modern agricultural and forestry practices were associated with smaller fire use, like the end of slush and burn farming and a dramatic reduction in the amount of burned area. Such studies, including Mártinez-Fernández et al. (2013), and a review by Bowman et al. (2009), prove that the variation in the occurrence of fires cannot be

NHESSD
1, 6291–6326, 2013

predicted by climate forcing alone, but that other aspects such as human behaviour and the effectiveness of fire detection and suppression systems must be taken into account too.

When assessing the response of fire danger to future changes in climate, fire indices are calculated from the output of climate models. Observational meteorological datasets can be used to assess fire danger in the past. These can take two forms: measurements made at the observing stations, which are typically transformed to a gridded dataset, such as the E-OBS dataset (Haylock et al., 2008), created by interpolating station values to the selected grid; or reanalyses, where datasets are created using the same methods as used in numerical weather forecast modelling analyses. In Europe, the reanalysis dataset ERA 40 (Uppala et al., 2005) is often used. ERA 40 covers the years 1957–2002 and has a spatial resolution of $2.5^{\circ} \times 2.5^{\circ}$. A similar dataset, ERA Interim (Dee et al., 2011), covers 1989 to the present with a higher spatial resolution of $1.5^{\circ} \times 1.5^{\circ}$.

Though weather is not the sole forcing mechanism of forest fires, it still remains as one of the key factors for explaining the spatial and temporal variability of fires. Therefore, in this study the main objective is to investigate whether the recent changes in climate have had a discernible impact on weather-related fire danger in Europe. Additionally, we aimed also at investigating the significance of fire-weather indices in forest fires in two test sites (Greece and Spain). To answer these questions we have examined the temporal variation of the danger as expressed by FWI due to the variation in meteorological conditions over different European regions during 1960–2012 using ERA 40 and ERA Interim datasets. In addition, we calculated the cross-correlation between the burned area and mean FWI values in the two Mediterranean countries mentioned.

NHESSD
1, 6291–6326, 2013

2 Material and methods

2.1 European level

Europe was divided into four regions (Fig. 1) and only the grid boxes containing land were studied. The area denoted as South Europe includes part of Northern Africa for this study. We used ERA 40 for the years 1960–1999 and ERA Interim for the years 1980–2012 at their native resolutions to calculate the Canadian FWI for each year during March–September, as this period comprehends the main fire season. The main parameters of interest were the mean (March–September) value of FWI, and the number of days when FWI was larger than 10 or larger than 30. In Southern Europe FWI values larger than 30 are common, whereas in the rest of the Europe they occur only very occasionally. The results for the exceedance of threshold were presented as probabilities in percent (%):

$$\text{Probability} = 100 \cdot [\text{no. of cases}/(\text{no. grid boxes} \cdot \text{no. of days})]. \qquad (1)$$

The input parameters required for deriving FWI are the mid-day temperature, relative humidity and wind speed, together with the precipitation sum of the previous 24 h. The sensitivity of FWI on these controlling parameters was demonstrated using two different datasets. First, the relationship between FWI and air temperature, wind speed, air humidity and precipitation for a meteorological station located in southern Finland (60°19′ N, 24°57′ E) during 1 April–31 October 1995 was analysed. In the second analyses, the relationship between mean March–September FWI and air temperature, and precipitation for the four areas used in the study (Fig. 1) calculated using ERA Interim data as input was depicted.

In the continent scale calculations the 12:00 UTC values were used. As the region used in the study is roughly from 5° W to 40° E the 12:00 UTC value means four different solar times and this creates some inaccuracy in the calculations. However, as we are now interested in long term temporal changes in FWI the exact numerical values are not that critical from that point as long as the method remains the same throughout the whole calculation period.

The calculation of FWI was performed with the R-package “fume” created by the Santander Meteorology Group (http://www.meteo.unican.es), which has been used by Bedia et al. (2012). The trend was analysed using the Mann–Kendal test and the gradient of the trend line was calculated using Sen’s slope estimate (Sen, 1968), utilising the Excel applications published by Salmi et al. (2002).

2.2 South-Mediterranean level

Total burned area statistics at national scale for Greece and Spain were available for the period 1960–2010. The Greek data is a subset from a national wildfire time series data (Koutsias et al., 2013) originally obtained from the National Statistical Service of Greece (NSSG), the Hellenic Forest Service (HFS), the Hellenic Fire Brigade (HFB) and Kailidis and Karanikola (2004). The Spanish data covered the 1961–2010 period and was obtained from the Spanish national forest fire statistics of the Ministry of Agriculture and Environment.

FWI estimations were originally calculated for the South using ERA 40 for the period 1960–1999 and ERA Interim for the period 1980–2010. To extend both periods to a common basis and allow comparisons with burned area statistics (1960–2010), we estimated the ERA 40/ERA Interim coefficient from their common period (1980–1999) and extended the respective FWI time series on the basis of the estimated coefficient for the missing years of each time series. Thus, we created two FWI time series, one corresponding to ERA 40 and one to ERA Interim for the period 1960–2010.

For the national level calculations, in Spain we calculated the FWI from June to September both from ERA 40 and ERA Interim datasets using only the grid cells located within peninsular Spain.

To identify possible abrupt shifts of the mean values of FWI in the time series, indicating distinct time periods, we applied the F statistic and the generalized fluctuation tests as described in Zeileis et al. (2003) and implemented in the R package “strucchange”

(Zeileis et al., 2002). We applied both tests with a 0.1 bandwidth resulting in 5 yr data window. To identify the optimal number of breakpoints we adopted the method described in Zeileis et al. (2003). Within the defined segments, based on the breakpoints, we analyzed the trend using the Mann–Kendal test and the slope of the trend line was calculated using the Sen's slope estimate.

Burned area values were ln transformed and the cross-correlation with FWI were estimated applying the modified Pearson's correlation coefficient accounting for the autocorrelation of the time series using the approach followed by Meyn et al. (2010) by calculating the effective sample size that arises when first-order correlation coefficient is considered. Additionally, cross-correlation between FWI and the untransformed burned area values were estimated by means of the non-parametric Spearman's coefficient accounting also the autocorrelation in the time series. The cross-correlation analysis has been made using ±3 lags (years) within the defined time segments in order to explore any bivariate lagged relationships between area burned and FWI.

3 Results

3.1 European-level

3.1.1 Response of mean FWI

The temporal variation of mean FWI values since 1960 (Figs. 2 and 3) displays a relatively large year-to-year variation. The March–September mean FWI is about 10 in the south, 4 in the east, 3 in the west and 2 in the north. The mean calculated for the whole Europe is almost 6. For the years 1980–1999 there is an overlap between ERA 40 and ERA Interim datasets, with good agreement in the values of FWI from both. In South Europe, the values based on ERA Interim are systematically slightly larger than from ERA 40, whereas elsewhere FWI from ERA 40 is systematically higher (Fig. 4). This may be due to the different number of grid boxes within different climatic zones;

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

NHESSD

1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

for example, the Mediterranean area is more influenced by the dry North African region when using ERA Interim.

According to the trend analyses for ERA Interim (Table 1) there is a significant upward trend at 95 % level for West Europe and at 99 % level for South Europe, and East Europe. The ERA Interim trend for all of Europe also has the same very high 99 % confidence. ERA 40 does not indicate any trend. The results show that during recent years, from approximately 1995 onwards, a tendency to higher fire danger can be detected in the time series in some areas. For the period 1960–1972 there is a negative trend in FWI depicting the natural variation of European climate.

3.1.2 Response of FWI exceeding selected thresholds

The time series for the number of days when FWI exceeds 10 or 30 (Fig. 5) show the same features as the time series for mean FWI (Fig. 3), with the number of days exceeding the selected threshold value becoming more frequent during the last 10 yr or so. No trend is indicated by ERA 40, which is only available until 1999.

According to the trend analyses for the number of days where FWI > 10 (Table 2), ERA Interim displays an upward trend significant at the 99 % level for South Europe, and East Europe, and an upward trend, significant at the 95 % level, for West and North Europe. The trend shown by ERA Interim for the whole of Europe reaches the 99 % confidence. For the number of days where FWI > 30 the trend is significant at the 90 % level. Again, there is no trend indicated by ERA 40. These results are very similar to the results obtained for the mean FWI values.

3.1.3 Sensitivity analyses

Looking at the long term temporal variation and change in air temperature we can detect the similar upward trend as in case of FWI. This trend is significant at 99 % level for the all analysed areas. On the other hand, precipitation values do not indicate any clear trend (Fig. 6). The rising trend of FWI can thus be explained by the rising temperature. If we look the relationship between FWI, air temperature, air humidity and wind speed in a single locations like shown in Fig. 7 depicting the relationship in northern Europe in Finland, we see that the correlation between the temperature and FWI is quite high ($r = 0.66$). In case of wind speed there is no clear correlation. High precipitation and relative humidity values are correlated with low FWI values. In case of larger geographical areas and mean seasonal values the relationship between FWI and temperature is clear for other areas except in the cool Northern Europe climate (Fig. 8). The dependence of FWI on precipitation is not that clear in case of Southern Europe where the precipitation values are already very low (Fig. 8).

3.2 South-Mediterranean national level

3.2.1 Greece

The analysis whether the mean of FWI based on ERA 40 and ERA Interim South changes over time, based on the F statistic and the generalized fluctuation tests, resulted in two breakpoints in years 1966 and 1997. Since breakpoints are estimated as the last observation in each defined segment, the FWI time series is therefore segments in three distinct periods, i.e.: 1960–1966, 1967–1997 and 1998–2012 (Fig. 9). Within the three distinct periods, only the FWI of ERA Interim had a positive trend using the Mann–Kendal-test and Sens's method, though at a significance level of 0.1 only. For the whole period (1960–2012), the FWI time series data, as modified for completing the missing years, show for both data sets (ERA 40 and ERA Interim) significant positive trends at $a = 0.01$, being in agreement with the trend observed in FWI of ERA Interim when only the original values are used covering the period 1980–2012 (Table 1). In the case of FWI of ERA 40 no trend is observed when only the original values are used covering the period 1960–1999 indicating that the observed positive trends either in FWI of ERA Interim (1980–2012) or in FWI of ERA 40 and ERA Interim of 1960–2012 (as modified for completing the missing years) results from the last couple of decades.

NHESSD

1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

The cross-correlation between FWI of ERA 40 and ERA Interim South and the untransformed and transformed (ln) burned area values at national scale in Greece within the period defined by the analysis of breakpoints (1967–1997) show significant, though not very high correlations, at lag 0 (Fig. 10).

3.2.2 Spain

The analysis whether the mean of FWI based on ERA 40 and ERA Interim data for Spain changes over time resulted in three breakpoints in years 1968, 1977 and 1999, defining therefore four distinct periods, i.e.: 1960–1968, 1969–1977, 1978–1999 and 2000–2011 for both datasets (Fig. 11). Here, it should be pointed out that the 1977 breakpoint could be an outcome of the combination between the extreme low FWI values observed during 1971 and 1972 (Fig. 11) and the short bandwidth that was selected for the analysis (5 yr). Within the three distinct periods, none of the data series found to have a significant trend using the Mann–Kendal-test and Sens's method. However, in the period defined when the last three sub-periods are merged to define 1969–2011 then FWI of both datasets, ERA 40 and ERA Interim, as modified for completing the missing years, showed significant positive trends at significance level of 0.001 similar to the positive trends observed of FWI time series data of ERA 40 and ERA Interim South. In the case of FWI of ERA 40 positive trend is observed when the original values are used covering the period 1969–2001 ($p = 0.001$) while in case of FWI of ERA Interim positive trend is observed when the original values are used covering the period 1980–2012 ($p = 0.01$).

For the cross-correlation analysis we defined the period from 1969 to 1999 (i.e., not considering the breakpoint 1978). This allows for the direct comparison of the outputs between the two different regions, since these periods correspond to the segments identified in Greece (see Sect. 3.2.1). The cross-correlation graphs between FWI of ERA 40 and ERA Interim South and the untransformed and transformed (ln) burned area values at national scale in Spain (Fig. 12) indicates significant correlations at lag

NHESSD
1, 6291–6326, 2013

0, higher as compared to those of Greek burned area values, however, again not very high.

4 Discussion

In this study we selected the period March–September as a suitable compromise for the main fire season across Europe. In Northern Europe the season usually starts in May at the earliest after snow has melted, whereas in Southern Europe the season is centred in the summer months, although in some areas out-of summer fires are also common. In some climatic regions, the weather from previous seasons can have an impact on fire activity (e.g. northeastern Iberian Peninsula as shown by Turco et al., 2013b), but for most of Europe's cooler and wetter climates, the impact of previous growing season conditions can be regarded as unimportant and we have not examined this factor in this study.

One of the main purposes of the study was to detect the climate change signal in fire danger and to assess its importance at two countries where fires are prevalent. A profound analysis of climatic trends is not within the scope of the present paper, yet it is made apparent that the FWI trends that are observed in this study are compatible with the general trend towards climatic features characterized by warmer temperatures and changed precipitation patterns in Europe (Chirstensen et al., 2007). The results of the sensitivity study (Figs. 7 and 8) prove that the rise of temperature, in case other parameters do not change, will lead to higher FWI values. This seems to have happened in Southern and Eastern Europe. In Northern and Western Europe temperature rise has not been that significant and while the precipitation has no clear trend the net effect is that FWI has not a long term trend either. There is a general tendency of increasing FWI values but with different intensity and significance level at the different European regions; and more strikingly, if different periods are considered. The latter is argued (a) by the lack of significant trends when the FWI is estimated using the ERA 40 data (1960–1999) which is contrasted by the positive trends when the FWI is estimated

NHESSD
1, 6291–6326, 2013

using the ERA Interim data and (b) by the different observed trends when time series are segmented on the basis of breakpoints. The observed trend in the mean values of FWI should be attributed to the observed trends of the meteorological parameters affecting this index.

More specifically and focusing in the studied regions, it has been shown that, generally and with significant variability among regions and seasons, rainfall amount in the Greek peninsula shows a trend to decline after 80's which is confirmed from various sources (Maheras et al., 2000; Pnevmatikos and Katsoulis, 2006; Feidas et al., 2007). This further supports the argumentation of Dimitrakopoulos et al. (2011c) regarding an increase in summer drought episodes. Warming trends, with the form of increasing daily air temperature extremes dominated central and Western Europe while in the same region, there are indications of insignificant increase in dry spells (Moberg and Jones, 2005). Additionally, Lloyd-Hughes and Saunders (2002) have drawn attention to drying tendencies over central Europe which are stronger for the winter period.

The identification of breakpoints in the various series analysed helped in defining homogenous periods in the FWI time-series that could be used to test trend-free cross correlations with fire statistics, rather than making a thorough analysis of the observed FWI variability. It is interesting to observe that the identified breakpoints of the FWI series for Greece that are presented in this paper (in 1966 and 1997 respectively) match, in the broad sense, the respective breakpoints of the homogenized air temperature time series of western Greece in early 70s and middle 90s (Kolokythas and Argiriou, 2013). Similarly, the mean annual air temperature in Greece was found to exhibit cooling trends from early 50s to mid-70s, then stabilizing at low levels before increasing again after early 90s (Nastos et al., 2011). Regarding precipitation, there were some marked breaks between the period 1971–1978 in some weather stations in the Ionian islands (north-west Greece) indicating shifts in the time-series towards reduced precipitation amounts during the latter periods (Kalimeris et al., 2012). According to Feidas et al. (2007) an approximation of the starting period of decreasing trend of the precipitation amounts in Greece is the decade between 1974 to 1984. Pnevmatikos and

Katsoulis (2006) identify a pronounced shift in rainfall amounts in 1980. The pattern of air temperature over Greece coincides with the observed patterns in FWI values and taking into consideration the high variability in precipitation pattern and trends, these are strong indications that the observed pattern of FWI over Greece is more tightly related to the long term air temperature fluctuations. It should be noticed though that further testing is required in order to identify whether the breakpoints are artificial and due to exogenous variables or if they actually indicate altering periods in the FWI values.

Correlations between area burned and FWI were apparent in both Spain and Greece. As it was shown here, the correlations between FWI and burned area, although significant were not very high and especially for Greece, they were similar to those estimated by Dimitrakopoulos et al. (2011b). This demonstrates, on the one side the causal effect of meteorological conditions on forest fires and on the other side the importance of other factors not related to climatic or meteorological conditions as for instance vegetation/fuel parameters (Viedma et al., 2009, 2006; Koutsias et al., 2013), physical parameters (Carmo et al., 2011) or socio-economic factors (Moreira et al., 2011; Martínez-Fernández et al., 2013). The differences between Greece and Spain in this respect can be explained firstly by the matter that FWI, estimated only from the grid cells corresponding to the area analyzed, performs better and justifying secondly again the important role of additional causal factors than meteorological conditions on forest fires. These difference could be also due to the fact that form Spain we use the fire-season FWI while for Greece the annual FWI.

The profound and tight relation between weather and area burned it has been demonstrated in numerous studies covering various parts and climate regions of the globe. Extreme fire weather is related to large fires in boreal ecosystems and sub-alpine forests (Beverly and Martell, 2005; Bessie and Johnson, 1995; Drobyshev et al., 2012). Similarly, in the Mediterranean region the positive links between area burned and various weather components that indicate drought are apparent. Variables that are most often correlating with burned area include simple weather parameters such

NHESSD
1, 6291–6326, 2013

as fire season precipitation (Vázquez and Moreno, 1993; Holden et al., 2007; Koutsias et al., 2013; Xystrakis and Koutsias, 2013; Pausas, 2004), air temperature (Vázquez and Moreno, 1995; Piñol et al., 1998) or indices which, combining various weather parameters, quantify drought and fire danger (Carvalho et al., 2008; Camia and Amatulli, 2009). Although correlation does not necessarily imply causation, the links are strong and consistent and the outputs of the present study also support this argumentation through the observed significant correlations. Such correlations between weather conditions and fire activity (including fire ignition and spread) are based on the control of weather in processes related to fuel moisture content and to the effect of wind in fire spread (Camia and Amatulli, 2009; Sullivan, 2009).

Large fires may account for more than 70 % of the total annual area burned (Ganteaume and Jappiot, 2013) and weather may be the dominant factor in determining fire spread (Moreira et al., 2011) with wind speed being identified as the main weather component of large forest fires in Greece (Dimitrakopoulos et al., 2011a) and California (Moritz et al., 2010), yet, a large part of variation remains unexplained if other parameters are excluded. The lack of topographic, socio-economic and landscape parameters may hamper correlations and this could be partially the reason of the considerably low correlation coefficients between FWI values and area burned in Greece (about 0.5). Such additional factors were found to play a major role in southern France (Ganteaume and Jappiot, 2013) where area burned is related to high vegetation cover. In central Spain landscape variability (discontinuity) was an important parameter for controlling fire-size, even if the vast majority of the fire events took place under severe fire weather with FWI larger than 30 (Viedma et al., 2009). The influence of landscape in fire spread is also indirectly revealed through the analysis of selectivity patterns of fires belonging to different size classes (Moreira et al., 2011). Large fires in Sardinia tend to selectively burn shrub- and grassland (Bajocco and Ricotta, 2008) and in central Spain large fires showed selectivity towards conifers and areas near settlements and roads (Moreno et al., 2011). Socio economic variables like unemployment and touristic pressure (Ganteaume and Jappiot, 2013) could directly linked to area burned or major social events could indirectly favor fuel conditions that could lead to large fire events as long as the fie is initiated (Koutsias et al., 2010). Similarly, humid-cool weather conditions could control fire initiation and spread even in the most fire prone ecosystems, indicating the dual role of weather in controlling fire size (Xystrakis and Koutsias, 2013). It can be argued that fire-weather triggers or inhibits the landscape, topographic and socioeconomic variables in emerging as dominant factors of fire spread (Moreira et al., 2011; Bradstock, 2010).

5 Conclusions

In this study we examined the temporal variation of climate and weather-induced fire danger in Europe using FWI. The results are in harmony with observed patterns of climate change, i.e., an increase in fire danger in Southern and Eastern Europe, and no clear signal elsewhere in Europe. Additionally, we found that a changes in fire-weather danger indices and are burned were cross-correlated in Greece and Spain when both series were divided in even periods, although the correlations were not very high. Though the meteorological conditions for inducing fire danger have changed area in some areas, forest fires have not necessarily followed suit, presumably due to other factors affecting them.

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NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

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1, 6291–6326, 2013
Temporal variations and change of forest fire danger in Europe in 1960–2012
A. Venäläinen et al.

Table 1. Trend and gradient of the mean March–September FWI values as calculated for the regions of Europe in Fig. 1 using the Mann–Kendal-test and Sen's method (Salmi et al., 2002) on ERA 40 and ERA Interim datasets. The following symbols indicate significance at level $\alpha = 0.01$ (***), $\alpha = 0.05$ (**) and $\alpha = 0.1$ (*).

Time series	First year	Last year	No. of years	Test Z	Signific.	Gradient
ERA 40 Europe	1960	1999	40	−0.570		−0.002
ERA 40 north	1960	1999	40	−0.501		−0.002
ERA 40 south	1960	1999	40	−0.245		−0.002
ERA 40 east	1960	1999	40	−1.456		−0.009
ERA 40 west	1960	1999	40	0.781		0.004
ERA Inter. Europe	1980	2012	33	4.663	***	0.023
ERA Inter. north	1980	2012	33	0.511		0.002
ERA Inter. south	1980	2012	33	3.672	***	0.034
ERA Inter. east	1980	2012	33	3.331	***	0.036
ERA Inter. west	1980	2012	33	2.030	*	0.012

NHESSD
1, 6291–6326, 2013

Table 2. Trend and gradient of the March–September FWI values higher than 10 or higher than 30 as calculated for the different areas of Europe (Fig. 1) using the Mann–Kendal-test and Sen's method (Salmi et al., 2002) and ERA 40 and ERA Interim datasets. The following symbols indicate significance at level $\alpha = 0.01$ (***), $\alpha = 0.05$ (**) and $\alpha = 0.1$.

Time series	First year	Last year	No. of years	Test Z	Signific.	Gradient
ERA 40 Europe > 10	1960	1999	40	−1.293		−0.016
ERA 40 south > 10	1960	1999	40	−0.687		−0.018
ERA 40 north > 10	1960	1999	40	−0.350		−0.003
ERA 40 west > 10	1960	1999	40	0.326		0.002
ERA 40 east > 10	1960	1999	40	−0.932		−0.039
ERA 40 Europe > 30	1960	1999	40	0.093		0.000
ERA 40 south > 30	1960	1999	40	0.117		0.001
ERA Inter. Europe > 10	1980	2012	33	4.571	***	0.115
ERA Inter. south > 10	1980	2012	33	3.641	***	0.183
ERA Inter. north > 10	1980	2012	33	2.046	*	0.019
ERA Inter. west > 10	1980	2012	33	2.650	**	0.031
ERA Inter. east > 10	1980	2012	33	3.331	***	0.173
ERA Inter. Europe > 30	1980	2012	33	2.557	*	0.009
ERA Inter. south > 30	1980	2012	33	2.557	*	0.024

NHESSD
1, 6291–6326, 2013

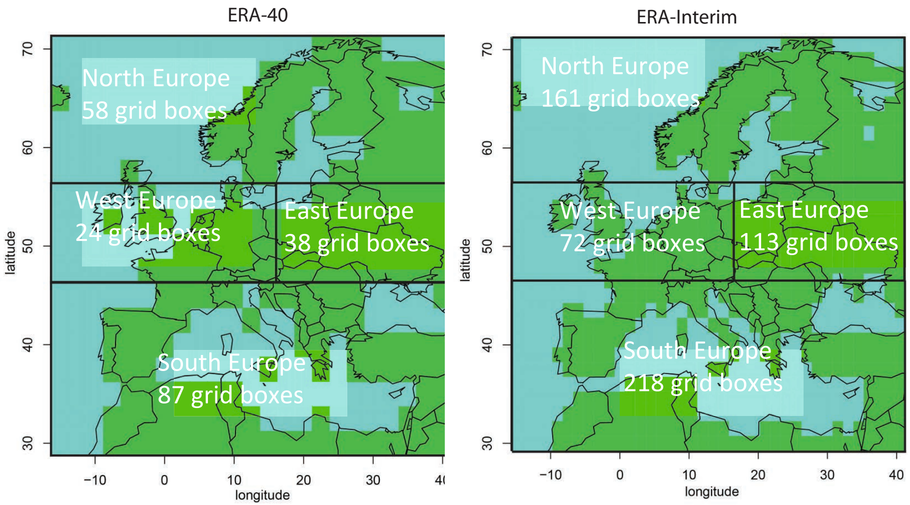

Fig. 1. The European regions analysed.

NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

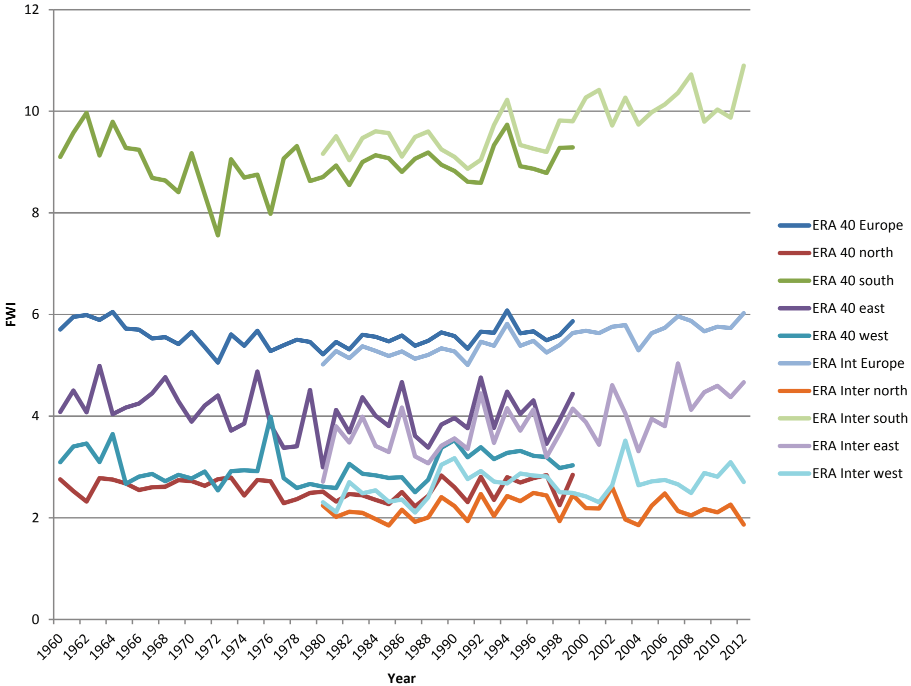

Fig. 2. The year-to-year variation of March–September mean FWI from ERA 40 and ERA Interim datasets for four selected areas (Fig. 1) and for the whole of Europe.

NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

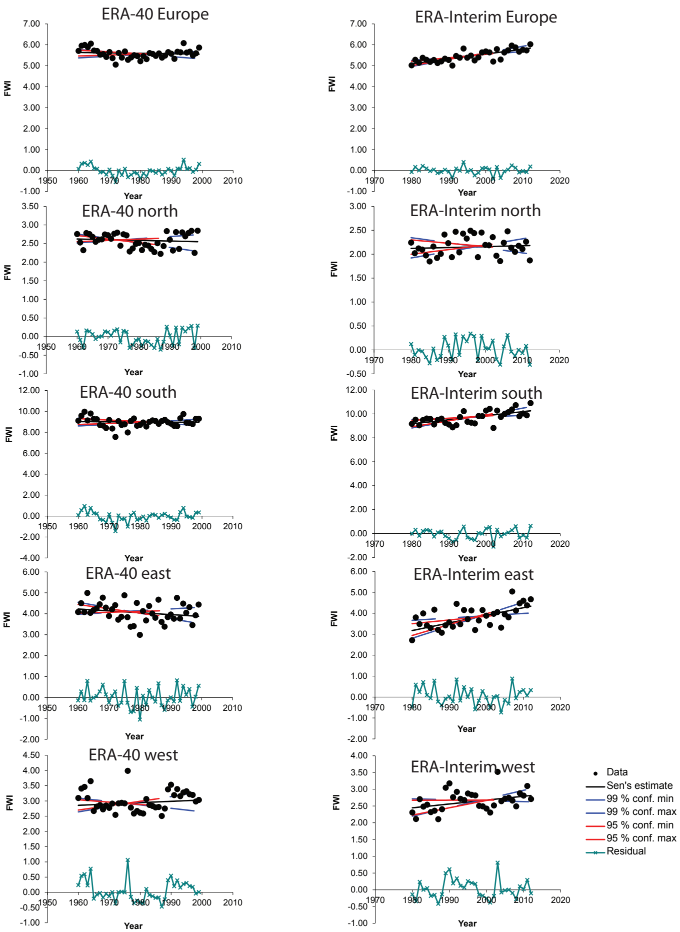

Fig. 3. Trend of March–September mean FWI calculated using ERA 40 and ERA Interim datasets for four selected areas (Fig. 1) and for the whole of Europe.

NHESSD
1, 6291–6326, 2013

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

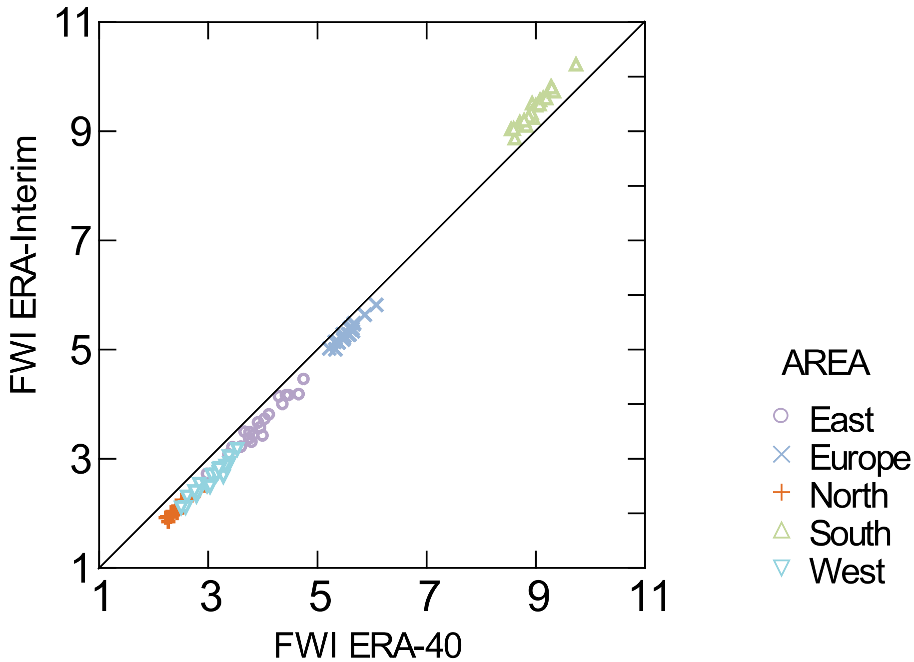

Fig. 4. Comparison of March–September mean FWI calculated using ERA 40 and ERA Interim datasets for four selected areas (Fig. 1) and for the whole of Europe based on the years 1980–1999.

NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

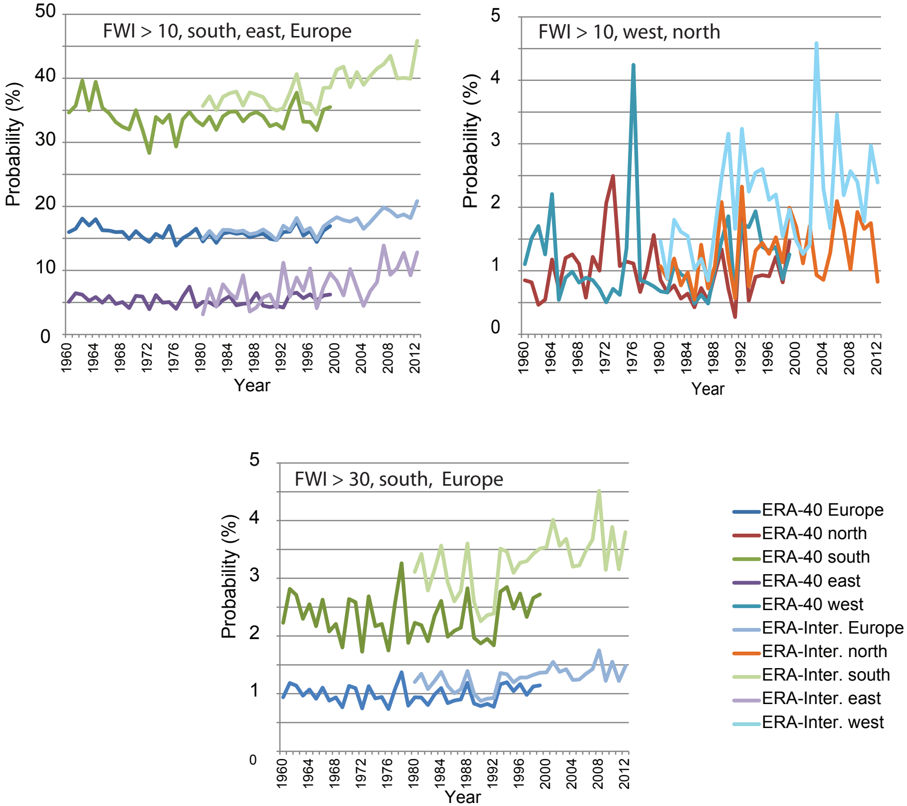

Fig. 5. The year-to-year variation of March–September FWI values above 10 from ERA 40 and ERA Interim datasets (upper panel), and FWI values above 30 calculated for south and for the whole Europe (lower panel). The value is expressed as a probability (Eq. 1).

NHESSD
1, 6291–6326, 2013

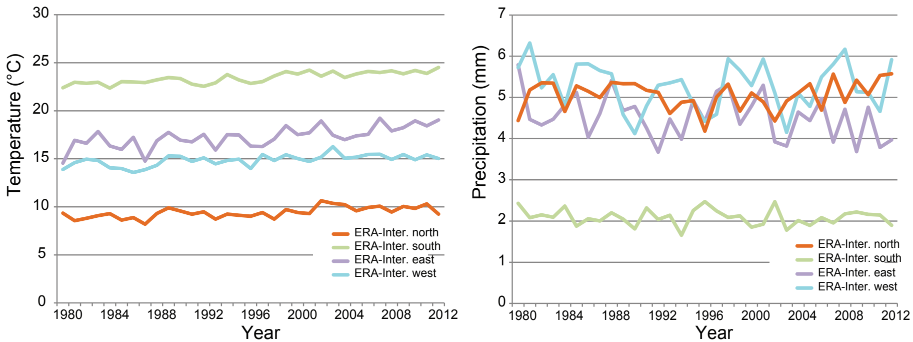

Fig. 6. The year-to-year variation of March–September daily mean temperature and daily mean precipitation from ERA Interim in four European regions (Fig. 1).

NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

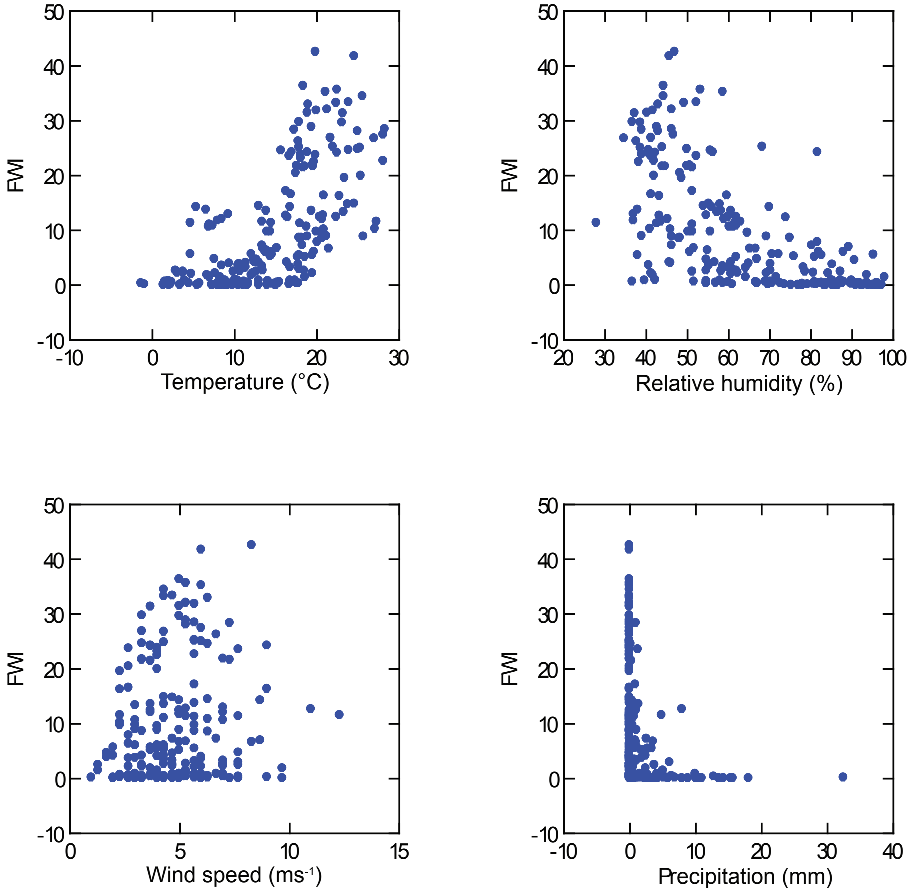

Fig. 7. The relationship between FWI and air temperature, wind speed, air humidity and precipitation for a meteorological station located in southern Finland (60°19′ N, 24°57′ E) during 1 April–31 October 1995.

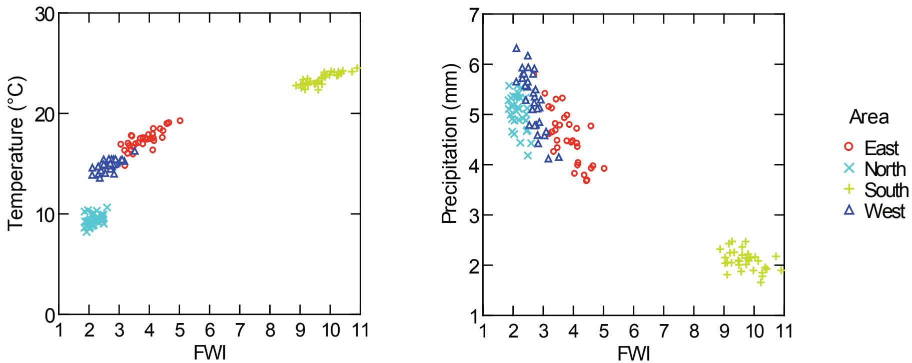

Fig. 8. The relationship between mean March–September FWI and air temperature, and precipitation for the four areas used in the study (Fig. 1) calculated using ERA Interim data as input.

NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

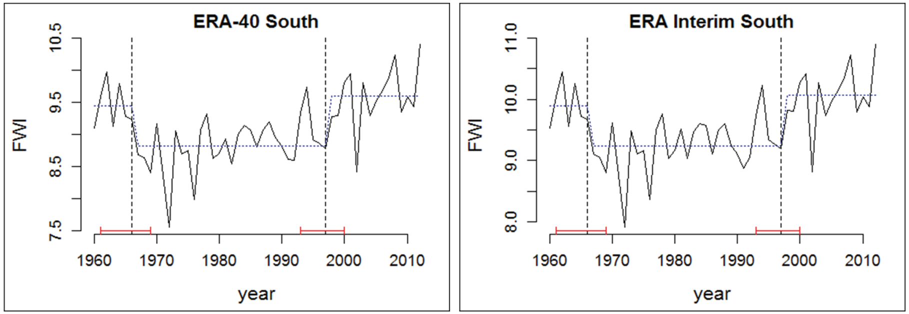

Fig. 9. Breakpoints of FWI time-series data based on ERA 40 and ERA Interim for South Europe. Vertical dotted lines correspond to breakpoints while red horizontal lines correspond to the 95 % confidence intervals of the estimated breakpoints. Blue lines represent the mean values of FWI for each identified segment.

NHESSD
1, 6291–6326, 2013

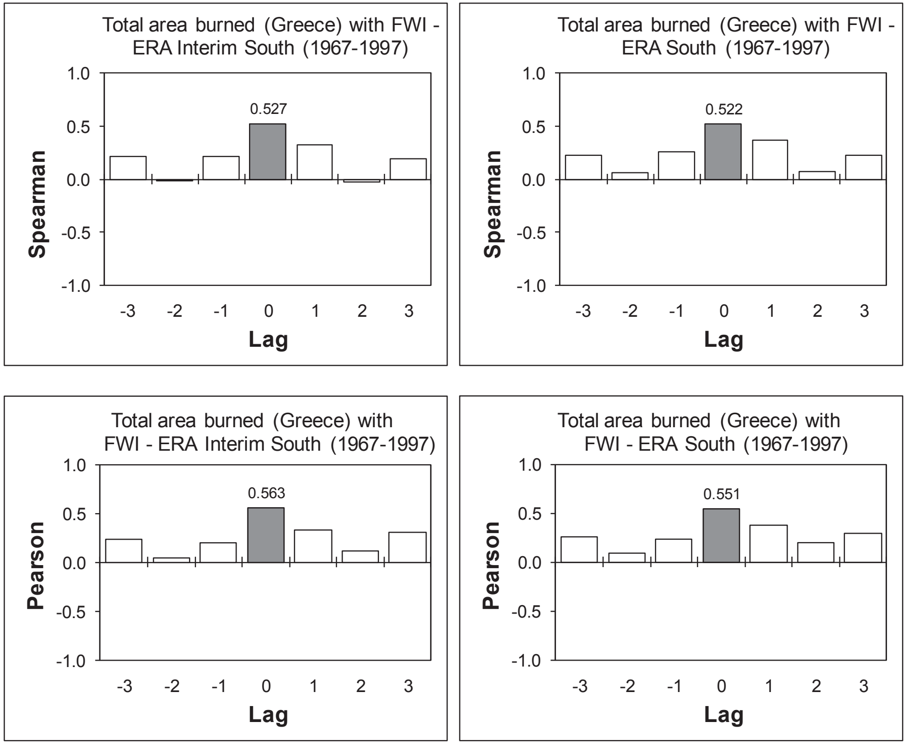

Fig. 10. Cross-correlation graphs between total burned area (original and ln transormed) at national scale in Greece and FWI values estimated from ERA south and ERA Interim south data for the period 1967–1997 (gray columns indicate significant values at 95 % confidence level).

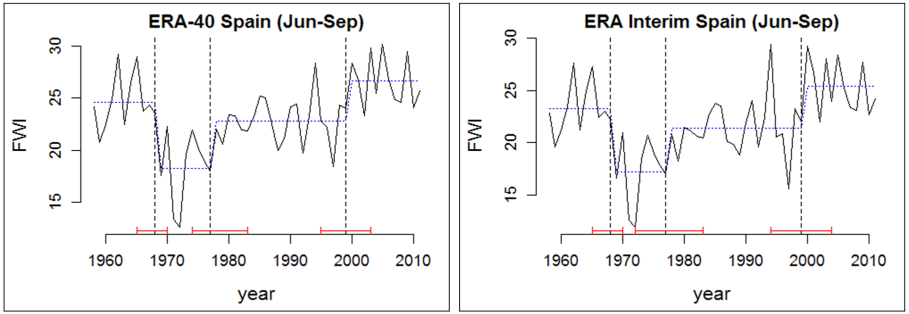

Fig. 11. Breakpoints of FWI time-series data based on ERA 40 and ERA Interim for Spain. Vertical dotted lines correspond to breakpoints while red horizontal lines correspond to the 95 % confidence intervals of the estimated breakpoints. Blue lines represent the mean values of FWI for each identified segment.

NHESSD
1, 6291–6326, 2013

Temporal variations and change of forest fire danger in Europe in 1960–2012

A. Venäläinen et al.

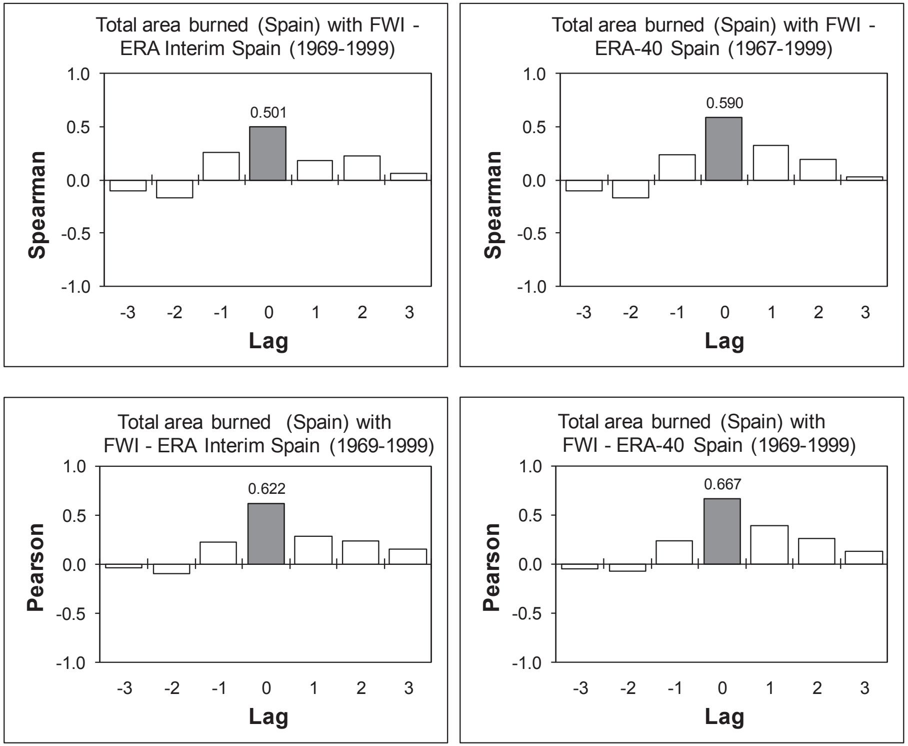

Fig. 12. Cross-correlation graphs between total burned area (original and ln transormed) at national scale in Spain and FWI values estimated from ERA south and ERA Interim south data for the period 1969–1999 (gray columns indicate significant values at 95 % confidence level).