CSIRO PUBLISHING

International Journal of Wildland Fire
http://dx.doi.org/10.1071/WF12003

On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010)

Nikos Koutsias[A,F], *Gavriil Xanthopoulos*[B], *Dimitra Founda*[C], *Fotios Xystrakis*[A], *Foula Nioti*[A], *Magdalini Pleniou*[A], *Giorgos Mallinis*[D] and *Margarita Arianoutsou*[E]

[A]Department of Environmental and Natural Resources Management, University of Ioannina, G. Seferi 2, GR-30100 Agrinio, Greece.
[B]Hellenic Agricultural Organisation 'Demeter', Institute of Mediterranean Forest Ecosystems and Forest Products Technology, PO Box 14180, Terma Alkmanos, Ilisia, GR-11528 Athens, Greece.
[C]Institute for Environmental Research and Sustainable Development, National Observatory of Athens, I. Metaxa & V. Pavlou Street, GR-15236 Penteli, Athens.
[D]Department of Forestry & Management of the Environment and Natural Resources, Democritus University of Thrace, Pantazidou 193, GR-68200 Orestiada, Greece.
[E]Department of Ecology & Systematics, Faculty of Biology, National & Kapodistrian University of Athens, Panepistimiopolis–Ilisia, GR-15784 Athens, Greece.
[F]Corresponding author. Email: nkoutsia@cc.uoi.gr

Abstract. Historical fire records and meteorological observations, spanning more than 1 century (1894–2010), were gathered and assembled in a database, to provide long-term fire–weather associations. We investigated the relationships between forest fire activity and meteorological parameters and sought to find temporal patterns and trends in these historical records and to identify any linkages between meteorological parameters and fire occurrence in the eastern Mediterranean region. Trend analysis of the time series revealed a statistically significant increase in the number of fires and air temperature, particularly after the mid-1970s. Fire occurrence, expressed as the annual number of fires and total burnt area, was strongly correlated with the mean maximum and the absolute maximum air temperature which, in turn, was related to the occurrence of summer heat waves. Total burnt area was also strongly negatively correlated with fire-season precipitation, and positively correlated with 2-year-lagged annual and summer precipitation, underlying the effect of precipitation in controlling fuel production and moisture. These findings support the argument that although annually lagged precipitation totals may have a marginal effect on fire risk by influencing biomass production and accumulation, the lag0 weather parameters are the main drivers of fire spread by directly controlling fuel moisture.

Additional keywords: autocorrelation, cross-correlation, forest fires, generalised least squares linear regression, Mann–Kendall trend test, Mediterranean Europe, Spearman correlation.

Received 4 January 2012, accepted 12 October 2012, published online 11 December 2012

Introduction

Fire is an integral part of many terrestrial biomes including the Mediterranean one, but it is also a major disturbance factor in ecosystems ranging from the boreal zone to tropical savannas and grasslands (Stocks *et al.* 2001; Mouillot and Field 2005; Pausas *et al.* 2008; Flannigan *et al.* 2009). Fire, as a disturbance factor in Mediterranean ecosystems, has an important role in the observed patterns of biodiversity (Cowling *et al.* 1996) and ecosystem function (Rundel 1981) and its role in structuring plant communities worldwide is also important (Bond *et al.* 2005; Pausas *et al.* 2008). Viedma (2008) and Moreira *et al.* (2011) reported that the effects of fire on ecosystems and landscapes may vary from region to region as a result of local fire history, regeneration patterns and topographic constraints. Observed increases in fire frequency, burnt area and fire severity, as well as a recently reported extension of the fire season (Flannigan *et al.* 2009; Dimitrakopoulos *et al.* 2011; Pausas and Fernández-Muñoz 2012; Zumbrunnen *et al.* 2012) have increased environmental concern and awareness within both society and the scientific community.

Fire regimes result primarily from the interaction of climate, topography, local microenvironments at finer spatial and temporal scales and land use–land cover (LULC) changes (Harrison *et al.* 2010). Human intervention may also affect these regimes. Extensive debate exists regarding the leading factors driving changes in fire regime focusing on LULC and climate. A straightforward answer to this becomes more difficult as regional fire regimes show great differences in the direction and amplitude of their changes (Flannigan *et al.* 2009). Yet, as Westerling *et al.* (2006) note, although LULC changes in the past may have increased sensitivity of fuels to climatic variability, climate on decadal scales defines vegetation characteristics, whereas climate on interannual scales affects flammability of live and dead vegetation. It has been reported that the major driving forces behind the observed changes in the Mediterranean basin include land abandonment and afforestation of former agricultural land that lead to increased fuel accumulation (Moreira *et al.* 2001; Pérez *et al.* 2003; Moreira *et al.* 2009), although the influence of climatic changes cannot be ignored (Piñol *et al.* 1998; Pausas 2004; Pausas *et al.* 2008). Additionally, variables defining landscape composition or proximity to human influence (Moreno *et al.* 2011), along with landscape structure (Viedma *et al.* 2009) and human activities such as agriculture and construction related to development projects, are also important underlying factors of fire risk in the Mediterranean (Martínez *et al.* 2009) and their spatial relationships may vary (Koutsias *et al.* 2010). Additionally, fire depends not only on structural factors but also on spatial factors considered as causal processes that reflect the degree of influence due to neighbourhood effects (Chou 1990; Vázquez and Moreno 2001), setting the role of space as an important factor.

In recent years human-induced climatic variability has been observed due to increased concentrations of greenhouse gases in the atmosphere (Flannigan *et al.* 2006). Greece being part of the eastern Mediterranean basin is an area particularly vulnerable to climatic change regarding temperature rise and increased fire risk (Giannakopoulos *et al.* 2011). Since the mid-1970s most regions of Greece experience significant positive temperature trends that are more pronounced in summer (Feidas *et al.* 2004; Founda *et al.* 2004; Philandras *et al.* 2008). Simulations of regional climate models for Greece suggest a further increase of summer air temperature accompanied by an extended dry period (Giannakopoulos *et al.* 2011). During the summer of 2007, Greece experienced two extreme and unprecedented events: the first was the occurrence of three extreme heat waves that hit the country from late June to the end of August. It is reported (Founda and Giannakopoulos 2009) that, with respect to daily mean, mean maximum and absolute maximum air temperature, the summer of 2007 was the warmest summer ever recorded at the station of the National Observatory of Athens (NOA) since Greek observations began (mid-19th century). The extremely high temperatures combined with a prolonged dry period triggered the second extreme event, which was the ignition of the most extensive and destructive forest fires in Greece's modern history (Founda *et al.* 2008). Koutsias *et al.* (2012) observed that part of these fires burnt non-fire-prone ecosystems thus indicating a departure from the burning patterns of recent history. Arianoutsou *et al.* (2010) also reported similar observations.

Understanding and quantifying the components that have shaped past fire regimes is crucial in the context of global change as a basis for predicting future changes (Zumbrunnen *et al.* 2011). Consequences of climate change in fire occurrence must be viewed in a spatially dependent context (Flannigan *et al.* 2006). Aggregating fire statistics for many different fuel types and climates may result in obscuring relationships between climate, fuel type and fire regime (Westerling *et al.* 2003). So far, few studies have explored changes in fire regimes, the majority of which were undertaken in North America (Hessl 2011). In the Mediterranean basin, studies on the trends and regimes of wildfires and their relationships with climate and weather parameters are documented in the west (Piñol *et al.* 1998; Pausas 2004; Carvalho *et al.* 2008; Pausas and Fernández-Muñoz 2012), whereas in the east only Dimitrakopoulos *et al.* (2011) have explored changes in fire regime and their correlation with the Standardised Precipitation Index (SPI) over a 36-year period.

The main aim of the current study was to identify long-term wildfire and climate and weather trends and associations in Greece, and investigate if and which weather parameters are correlated with historical fire records over a period spanning more than a century. To isolate socioeconomically imposed variability in fire regimes, the overall study period was split into three time windows. The availability of such historical data gives a unique opportunity to study long-term wildfire–weather interactions during the last century in a Mediterranean region.

Data and methods

Study area and data

Description of the study area

Greece occupies the southernmost part of the Balkan Peninsula and covers an area of ~132 000 km^2. The insular part of the country accounts for more than one-fifth of its total area and comprises more than 2000 islands (only 227 of which are inhabited) (Strid and Tan 1997). In total 80% of Greece consists of mountains or hills, making it the third most mountainous country in Europe (Dax and Hovorka 2005). The climate of Greece can be distinguished into five broad categories corresponding to five climatic regions (Mariolopoulos 1938): (1) Mountain region with long, harsh winters and short, rainy summers; (2) Continental region, with a climate intermediate between Mediterranean and central European; (3) Coastal Mediterranean region with mild summers; (4) Continental Mediterranean region characterised by extended summer drought and (5) Desert-like region in the south-eastern parts of the island of Crete. The most extensive ecosystems are the Mediterranean-type which account for 40% of the country's surface area (Arianoutsou and Diamantopoulos 1985). Greece has the tenth longest coastline in the world (15 000 km in total, 7300 km of which are continental and 7700 km belong to its more than 2000 islands). The country's population is ~11 million (2001 census data).

The dominant vegetation types affected by fires, according to official fire records between 1985 and 2004 (Hellenic Forest Service), are phryganic ecosystems (32.3% of the total burnt area), *Pinus halepensis* (15.4%) and *Pinus brutia* (6.2%) forests, *Quercus coccifera* shrublands (12.2%) and grasslands (7.4%).

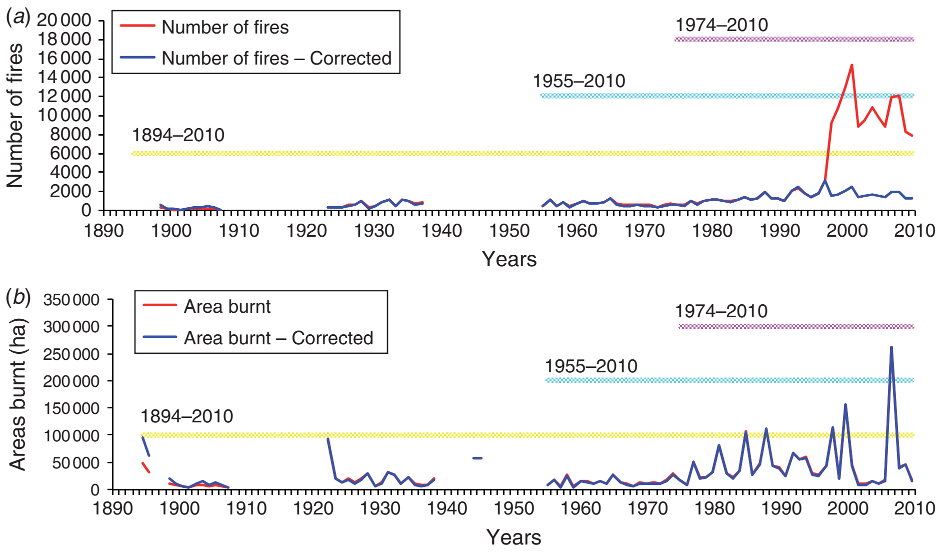

Fig. 1. Historical time series of fire occurrence in Greece during the period 1894–2010: (*a*) recorded and corrected number of fires, (*b*) recorded and corrected area burnt.

Additionally, 10.3% of the total burnt area was recorded in forests under regeneration where no information on the dominant affected vegetation types was provided.

Wildfire time series data

National wildfire time series data were obtained from the National Statistical Service of Greece (NSSG), the Hellenic Forest Service (HFS), the Hellenic Fire Brigade (HFB) and Kailidis and Karanikola (2004). These data, extending back to 1894, include the number of fires and the corresponding burnt area, summarised on a yearly basis (Fig. 1). To standardise fire data relative to the current areal size of Greece (132 000 km^2), for the period 1894–1912 the variables 'number of fires' and 'area burnt' were adjusted to the country's area at that time (63 211 km^2) by multiplying by 2.088 (=132 000/63 211). Additionally, data provided by HFB on the number of fires for the 2000–10 period were modified in order to standardise them with earlier data recorded by the HFS. In 1998 the responsibility for fire fighting in Greece changed from the HFS to the HFB. The HFB database contains all non-urban fires thus resulting in a much higher number of fires than that recorded previously by the HFS, which included only fires that burnt at least partially on forest lands. The correction has been implemented by adjusting the average value across the HFB recroding period to match the average value of the time series data provided by the HFS.

Meteorological time series data

Time series of meteorological data extending back to the end of the 19th century, were acquired from the historical meteorological station of the NOA (latitude 37°58.3′N, longitude: 23°43′E, altitude: 107 m above sea level). These data include monthly values of mean, mean minimum, mean maximum, absolute minimum[A] and absolute maximum[B] air temperature, as well as monthly precipitation totals for each year (Fig. 2). Yearly values were estimated and used for the correlation analysis with time series of wildfire data. Monthly precipitation values were also aggregated to seasonal and to fire-season precipitation and examined for correlation with wildfire statistics.

Methods

To isolate socioeconomically imposed variability on fire regime, and minimise the effect of any incompatibilities arising from the different methods used historically to record fire statistics, three time windows were analysed separately. The first window covers the 1894–2010 period, which is the full period of available data. In this series there are two data gaps, from 1908–21 and from 1939–54, approximately coinciding with periods of war. The second time window (1955–2010) coincides with the modern period during which the NSSG resumed systematically collecting statistical data including data on forest fires. The third time window (1974–2010) commences when the country's 7-year dictatorship ended and the third Hellenic democracy period began. The mode of economic development followed since 1974 induced significant socioeconomic changes (e.g. increase in personal income, rural abandonment and population concentration in large cities and development of wildland–urban interface areas).

Trends

To investigate possible trends in the time series data, the Mann–Kendall trend test (Hipel and McLeod 1994) and the nonparametric Theil-Sen approach (Meyn *et al.* 2010), properly modified to account for autocorrelation of the time series data

[A]Lowest daily minimum temperature observed during a given calendar year.
[B]Highest daily maximum temperature observed during a given calendar year.

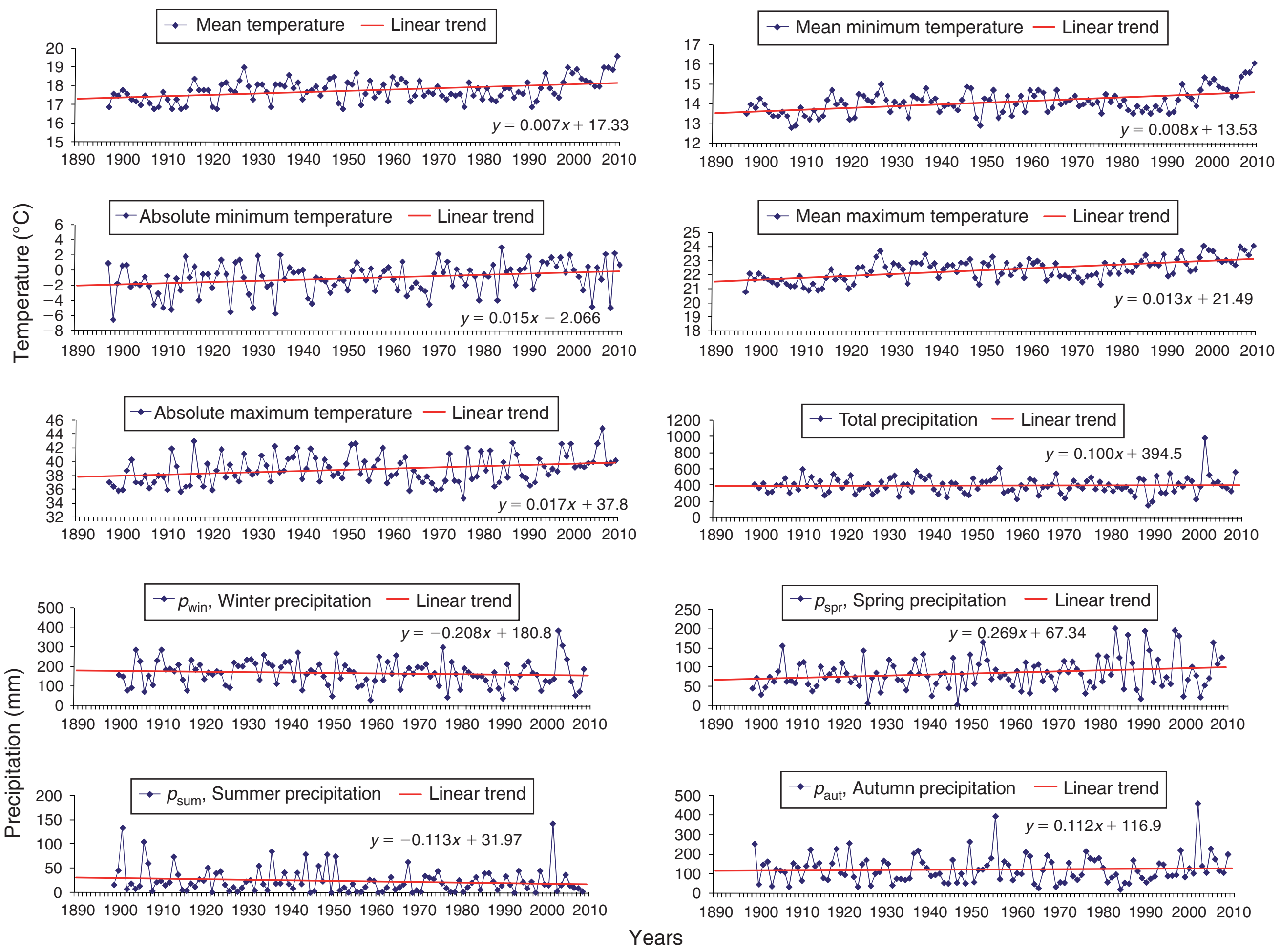

Fig. 2. Time series of historical meteorological data as acquired from the National Observatory of Athens (NOA).

(Sousa *et al.* 2011) were applied. For the trend analysis we used MAKESENS 1.0 (Salmi *et al.* 2002) and also a Matlab script developed by Simone Fatichi (Fatichi 2011).

Correlation and cross-correlation

Time series of fire and weather data were first analysed on the basis of their autocorrelation functions (ACF) in order to explore their patterns of serial dependence among the different time periods under consideration. ACF. diagrams were constructed by means of the 'TSA' package in R (R Development Core Team 2011).

The relationship between fire occurrence (number of fires, total burnt area) and selected meteorological parameters was investigated using the Spearman rank correlation coefficient, a non-parametric measure of bivariate relationships. Kendall's non-parametric tau-b correlation coefficient was also used. To account for autocorrelation in the time series data, we used the approach followed by Meyn *et al.* (2010) by calculating the effective sample size that arises when the first-order correlation coefficient is considered.

Similarly, cross-correlation diagrams of ±7 lags (years) were created based on Pearson's coefficient, corrected for the autocorrelation in time series data (1894–2010) in order to explore any bivariate lagged relationships between area burnt and weather variables. Highly skewed time series – total burnt area, number of fires, fire-season precipitation and summer precipitation – were log-transformed. Time series that reflected significant trends during the measuring period were detrended by means of ordinary least-squares (OLS) regressions. Additionally, cross correlations between area burnt and selected weather variables for the periods 1955–2009 and 1974–2009 (complete time series) were also estimated. For these periods, time series that were reflecting trends were detrended by means of OLS regression. To avoid spurious correlations resulting from autocorrelation of time series, pre-whitening adopting the 'system' approach (Chatfield 2004) was performed. The weather-related times series, which are regarded as 'input series' of the system, were pre-whitened by means of a 10-order autoregressive model (AR_{10}) in order to remove serial correlation, and the same autoregressive model was used to filter the fire-related series which are regarded as the 'response series' (Cryer and Chan 2008; Mills 2011). Pre-whitening was performed with the 'TSA' package in R (R Development Core Team 2011).

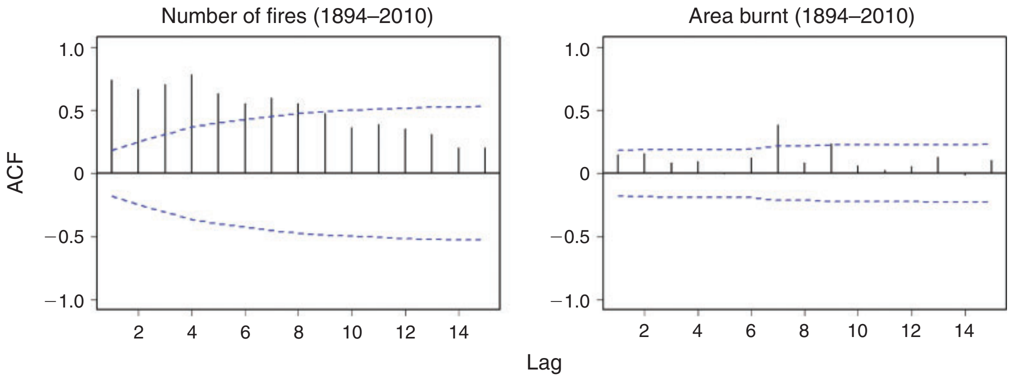

Fig. 3. Autocorrelation function (ACF) diagrams for the historical data of fire records (number of fires and area burnt) in Greece for the period 1894–2010. Dashed lines indicate the 95% confidence intervals estimated by means of the Bartlett equation (Hipel and McLeod 1994).

Regression

Following identification of the correlation between meteorological and fire data series, a regression model was built using burnt area as the dependent variable and various meteorological variables as predictors. Previous to model fitting, burnt area was log transformed in order to reduce the effect of outliers, as for example the year 2007, during which the recorded burnt area was extremely large (see Fig. 1). A preliminary OLS linear model was fitted in order to perform various regression diagnostics, including identification of significant predictors through a forward-backward stepwise selection using the Akaike Information Criterion (AIC), estimation of predictor importance and multicollinearity tests, by means of the variance-inflation factors, the condition index and the variance decomposition proportions. Having defined the most appropriate OLS model, a generalised least-squares (GLS) linear model taking into account the residual autocorrelation was built through maximising the log likelihood (Chatfield 2004). To account for residual autocorrelation, the most suitable autoregressive–moving average (ARMA) model was fitted, based on ACF, Partial Autocorrelation Function (PACF) diagrams and the AIC criterion. Analyses were performed using the 'MASS', 'perturb', 'nlme', 'relaimpo' and 'TSA' packages in R (R Development Core Team 2011).

Results

Autocorrelation structures

Wildfire data series

Different autocorrelation structures for the number of fires and the annual total burnt area during the three time periods under consideration were identified. The total annual number of fires showed a significant autocorrelation for time lags of up to 9 years in the period 1894–2010 (Fig. 3) and up to 5 and 4 years for the respective periods 1955–2010 and 1974–2010 (Fig. S1 of the Supplementary material). The autocorrelation patterns were very similar in all three periods, presenting a peak of significant correlations at 4 years, thus indicating a robust 4-year periodicity.

For the burnt area, statistically significant autocorrelation was evident with a 7-year timespan for the time periods 1894–2010 (Fig. 3) and 1955–2010 (Fig. S1) but for the period 1974–2010, the distinct peak at lag7 was not statistically significant. It is worth noting the changes in autocorrelation patterns of area burnt among the different time periods: although the first 6-year autocorrelation coefficients of burnt area during the periods 1894–2010 (Fig. 3) and 1955–2010 (Fig. S1) were positive, the respective autocorrelation coefficients during the period 1974–2010 were negative (Fig. S1).

Meteorological data series

Temperature. Regarding the meteorological variables, strong and significant autocorrelations were observed for all temperature-related weather variables and for all considered periods (Figs. 4 and S2). It appears that averaging the temperature smoothes variability and enhances the autocorrelation in the time series. Depending on the variable examined, significant positive autocorrelations were estimated up to 9 years. The absolute maximum air temperature reflected a positive significant peak at lag5 for the first two periods (also apparent, although not significant, in the period 1974–2010).

Precipitation. The magnitudes and significance of the serial correlations of the various precipitation-related variables (presented in Fig. 4 for the period 1894–2010 and in Fig. S2 for the periods 1955–2010 and 1974–2010) were neither large nor stable. Instead, they showed high inter-annual variability, which was not clearly related to previous or following years. It is, however, interesting to note the peaks at autocorrelation patterns of winter and spring precipitation at lag7 in all examined time windows, although the correlations were not statistically significant. Similar patterns can be also seen when other aggregated seasonal precipitation totals are considered.

Trends

Both number of fires and area burnt reflected a clear, significant positive trend for all periods under consideration, with the exception of area burnt during the period 1974–2010 (Table 1). The same pattern was observed for all temperature variables with the exception of absolute minimum air temperature during the period 1974–2010. The most intense trends were observed for mean maximum air temperature. In

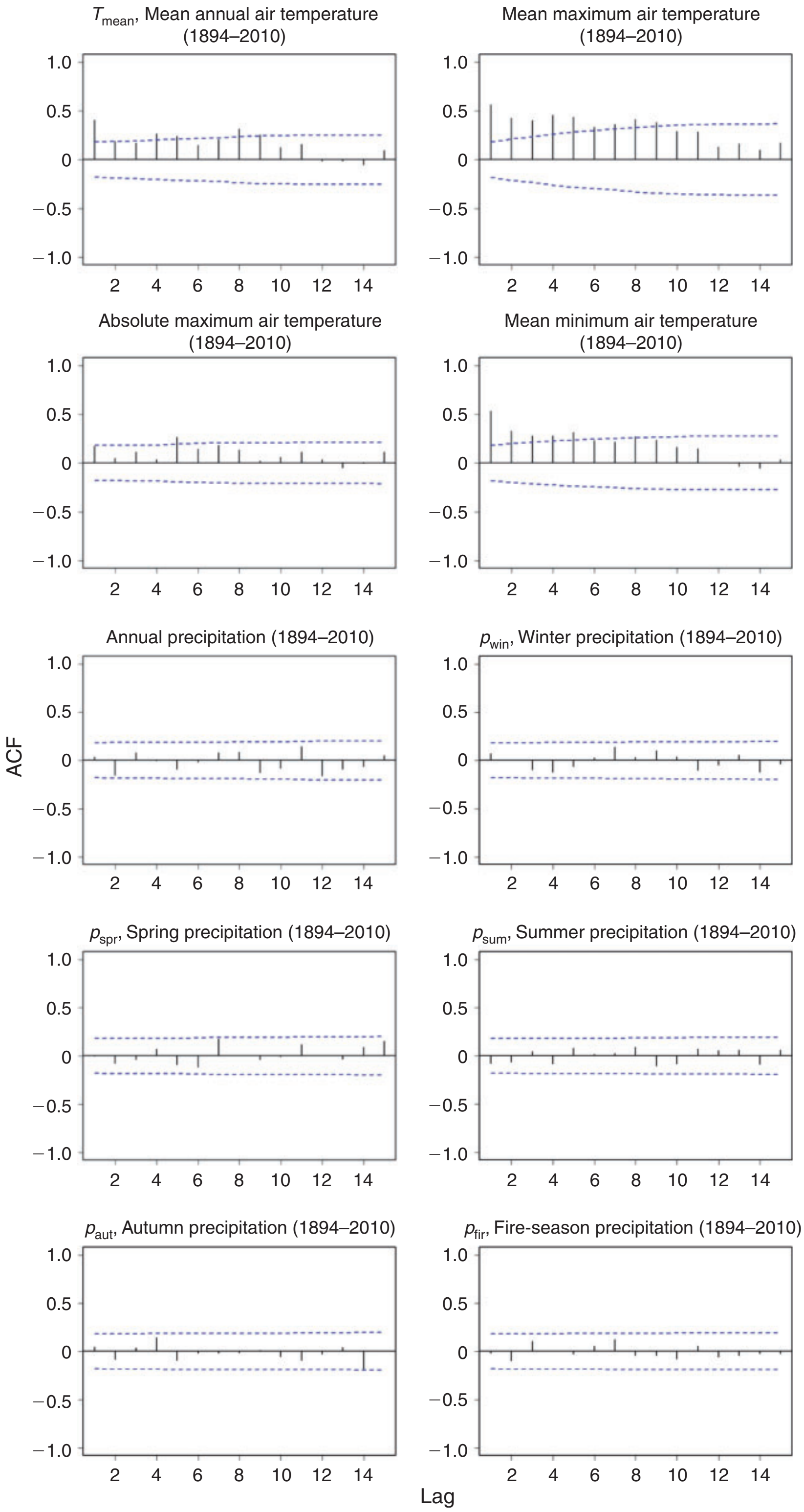

Fig. 4. Autocorrelation function (ACF) diagrams for the historical meteorological data of selected temperature and precipitation parameters in Greece for the period 1984–2010. Dashed lines indicate the 95% confidence intervals estimated by means of the Bartlett equation (Hipel and McLeod 1994).

Table 1. Output of the trend analysis of the time series data

Trends are significant at +, <0.1; *, <0.05; **, <0.01; ***, <0.001

Time series	1894–2010 Mann–Kendall trend Test Z	Significant with autocorrelation	Sen's slope estimate Q	B	1955–2010 Mann–Kendall trend Test Z	Significant with autocorrelation	Sen's slope estimate Q	B	1974–2010 Mann–Kendall trend Test Z	Significant with autocorrelation	Sen's slope estimate Q	B
Number of fires[A]	8.35***	Y***	13.34	8.91	6.18***	Y***	24.64	449.98	4.43***	Y***	29.63	841.36
Area burnt[A]	3.70***	Y***	179.89	6233.44	3.83***	Y^{+}	619.55	6050.79	0.14	N	77.04	30 220.07
Mean air temperature	3.77***	Y***	0.01	17.41	2.68**	Y**	0.01	17.43	4.19***	Y***	0.04	17.20
Mean minimum air temperature	4.55***	Y***	0.01	13.60	2.92**	Y*	0.02	13.78	4.17***	Y***	0.05	13.51
Absolute minimum air temperature	2.86**	Y***	0.02	−1.80	2.12*	Y*	0.03	−1.23	1.21	N	0.03	−0.56
Mean maximum air temperature	6.58***	Y***	0.01	21.53	4.51***	Y***	0.03	21.93	4.21***	Y***	0.04	22.09
Absolute maximum air temperature	3.04**	Y**	0.02	37.57	2.84**	Y**	0.05	37.22	2.77**	Y**	0.09	37.15
Total precipitation	−0.04	N	−0.01	393.78	0.994	N	0.92	354.25	0.790	N	1.20	365.35
Winter precipitation	−1.57	N	−0.31	186.85	−0.37	N	−0.20	163.10	−0.12	N	−0.27	156.77
Spring precipitation	1.74^{+}	Y*	0.21	68.10	0.79	N	0.38	76.30	−0.0	N	−0.09	83.29
Summer precipitation	−1.38	N	−0.06	21.17	0.696	N	0.09	11.94	−0.44	N	−0.14	19.87
Autumn precipitation	0.36	N	0.07	107.32	0.97	N	0.55	88.05	1.64^{+}	Y^{+}	1.57	76.89

[A]Values for earlier periods have been standardised for areal size of Greece post-1912 (see text).

Table 2. Spearman's correlations between the number of fires and total burnt area with selected parameters of weather variables

Shaded cells indicate the highest absolute correlation coefficients. Values for earlier periods were standardised for areal size of Greece post-1912 (see text). Correlations are significant at *, <0.05; **, <0.01

Spearman's correlation	1894–2010 Number of fires	1894–2010 Area burnt	1955–2010 Number of fires	1955–2010 Area burnt	1974–2010 Number of fires	1974–2010 Area burnt
Mean temperature	0.405**	0.225*	0.369**	0.133	0.478**	0.107
Mean minimum temperature	0.406**	0.186	0.328*	0.063	0.461**	0.018
Absolute minimum temperature	0.227*	0.201	0.231	0.270*	0.266	0.249
Mean maximum temperature	0.657**	0.442**	0.625**	0.429**	0.542**	0.271
Absolute maximum temperature	0.501**	0.451**	0.489**	0.429**	0.414*	0.368*
Total precipitation	−0.008	−0.181	−0.039	−0.221	−0.093	−0.355*
Winter precipitation	−0.074	−0.174	−0.145	−0.306*	−0.151	−0.384*
Spring precipitation	0.180	0.227*	0.068	0.229	−0.053	0.176
Summer precipitation	−0.206	−0.281*	−0.029	−0.131	−0.063	−0.295
Autumn precipitation	−0.013	−0.160	−0.014	−0.184	0.080	−0.152
Fire-season precipitation	−0.178	−0.385**	−0.215	−0.371**	−0.172	−0.547**

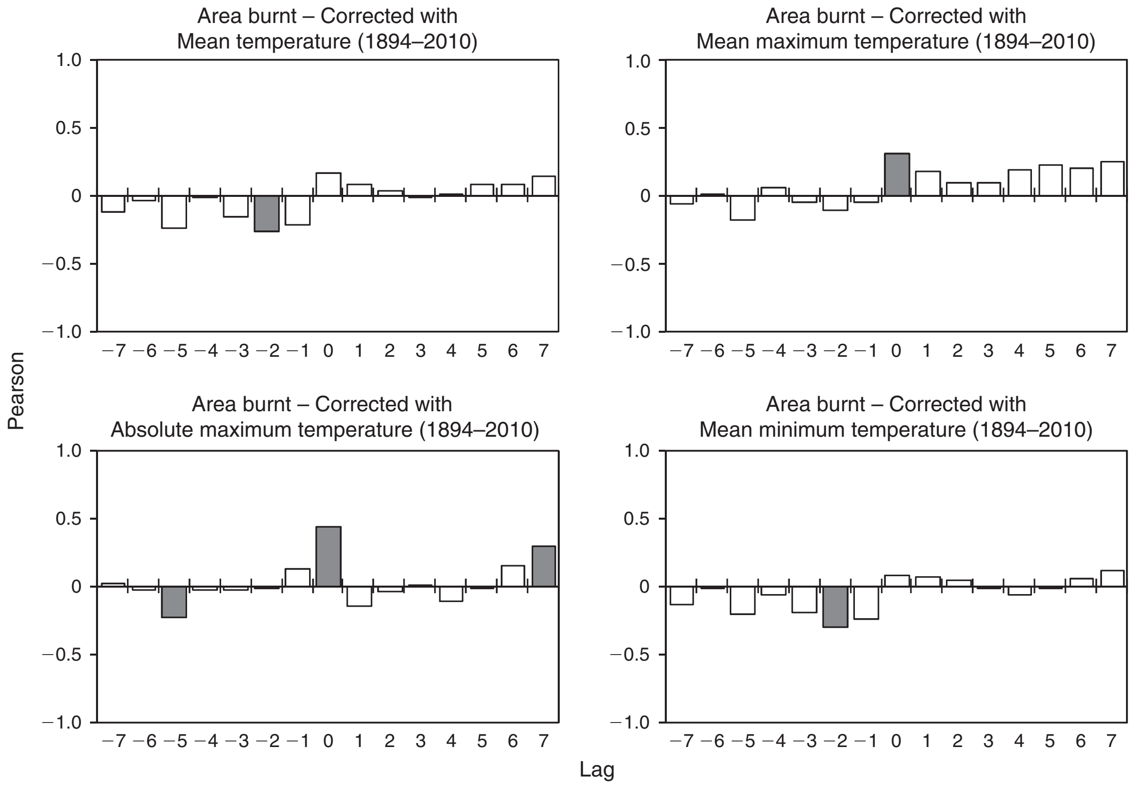

Fig. 5. Cross-correlation graphs between corrected area burnt and selected temperature parameters in Greece for the period 1894–2010 (grey columns indicate significant values at 95% confidence level).

contrast, mixed trends were observed in seasonal precipitation and these deserve further interpretation. Although total annual precipitation showed a negative (though not significant) long-term trend, spring precipitation tended to increase whereas summer precipitation tended to decrease in analysis based on the period 1894–2010 (Fig. 2, Table 1). This could affect fire occurrence because spring precipitation enhances biomass productivity and allows fine fuel to accumulate, whereas summer precipitation is negatively associated to fire occurrence because it increases fuel moisture that reduces fire spread.

Spearman's correlation

The correlation coefficients showed similar patterns in all three studied time periods (Table 2). Mean and absolute maximum air temperatures showed consistently high correlation coefficients with both area burnt and number of fires, for all periods under consideration. Among precipitation-related variables, fire-season precipitation – which is the sum of the precipitation for the months May–October – outperformed the rest of the variables in all time periods considered, in correlating with area burnt and number of fires, with the exception of number of fires during the period 1894–2010. It is also worth noting that spring and summer precipitation respectively were positively and negatively associated to burnt area. No differences were observed between the results of the Spearman and Kendall correlation analyses (calculated but not presented here).

Cross-correlations

Temperature

Based on the cross-correlation analysis, at lag0, all correlations between area burnt and temperature variables were positive, indicating that high air temperatures are associated with large area burnt (Fig. 5 for period 1894–2010 and Fig. S3 for periods 1955–2010 and 1974–2010). Significant correlations were observed between area burnt and absolute maximum and mean maximum air temperature. As with autocorrelation graphs, averaging the values smoothes the numbers and therefore any possible existing relationships weaken or disappear. Positive correlations between air temperature and burnt area were also reflected for all other periods under consideration (see Fig. S3) and similarly, the mean and absolute maximum air temperatures were the two variables with the highest correlation coefficients, having significant correlations with burnt area.

Precipitation

Cross-correlation between precipitation totals and area burnt reflected various patterns, depending on seasonal aggregation of precipitation totals and the period under consideration (Fig. 6 for the period 1894–2010 and Fig. S3 for periods 1955–2010 and 1974–2010). In more detail, total annual precipitation appeared to be significantly negatively correlated with the total burnt area for all examined periods. Winter precipitation was negatively correlated with area burnt, and significantly so for the periods 1955–2010 and 1974–2010 (Fig. S3). Spring precipitation,

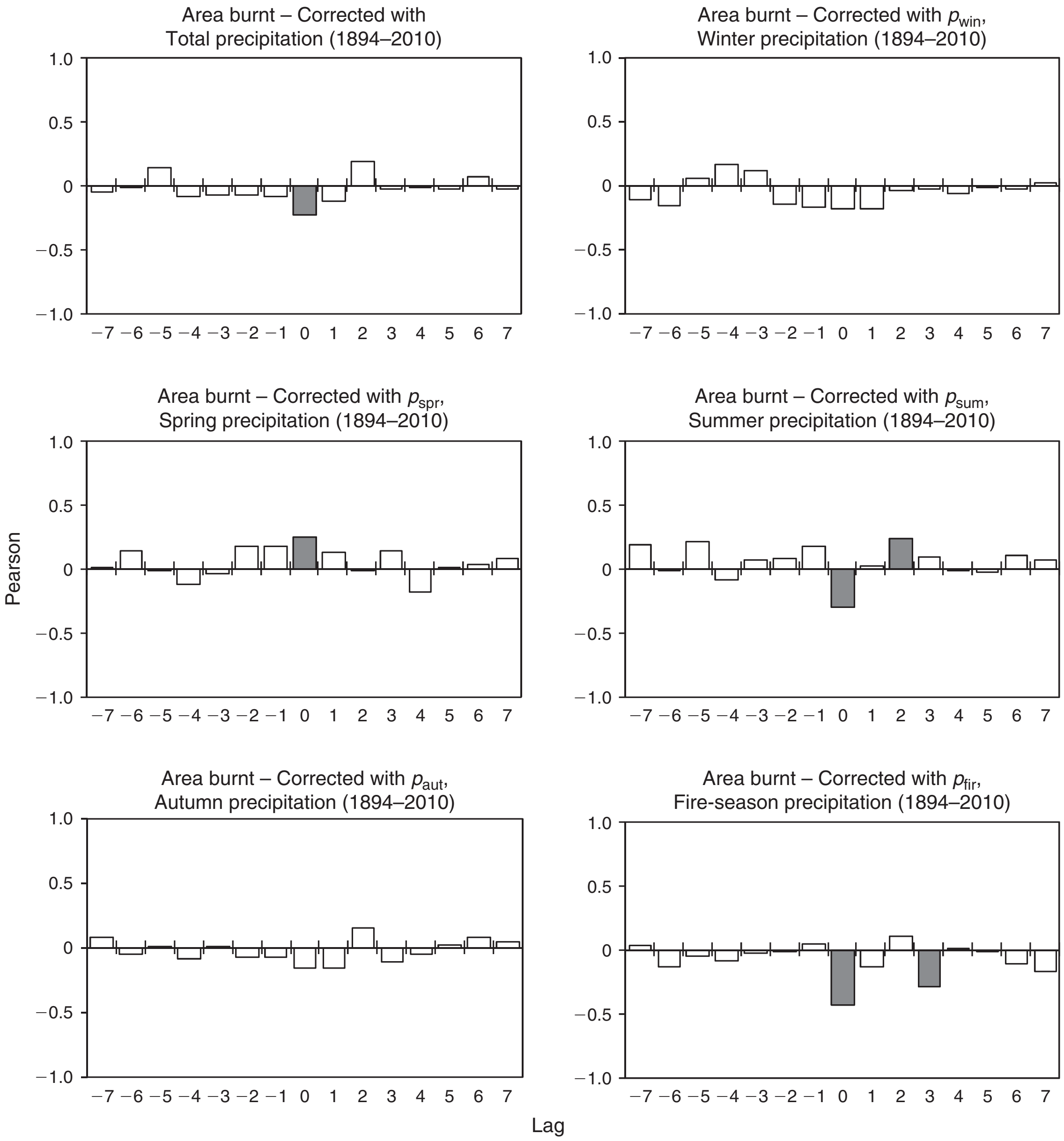

Fig. 6. Cross-correlation between corrected area burnt and selected precipitation parameters in Greece for the period 1894–2010 (grey columns indicate significant values at 95% confidence level).

coinciding with the vegetation growth period, was positively correlated with burnt area. This correlation was significant for the period 1894–2010, and almost so for the other two periods under consideration. It is worth noting that spring precipitation reflected positive correlations with area burnt for all periods under consideration at zero to four. Summer precipitation was negatively correlated with total annual area burnt, but this correlation was significant only for the period 1894–2010. Finally, fire-season precipitation had the highest (in absolute values) negative correlation coefficients with area burnt, which were significant for all time periods under consideration.

Additionally, from Fig. 6, it can be observed that both total annual as well as summer precipitation were positively correlated with the burnt area at a 2-year time lag, indicating a possible relationship between lagged precipitation and burnt area, a similar finding to that of Pausas (2004). However, this lagged correlation was found to be significant only for the summer precipitation. The same pattern was also apparent for the other periods under consideration.

Regression

Through the preliminary OLS linear model, four predictors were identified as significant, namely mean maximum air temperature, absolute maximum air temperature, mean air temperature and fire-season precipitation. Their importance, as estimated using various methods, is summarised in Fig. 7. The importance of mean maximum air temperature is especially apparent given the high percentage of variance accounted for.

Collinearity tests (Table 3) resulted in a Variance Inflation Factor (VIF) of ~5 for mean air temperature and mean max air temperature – much lower than the value of 10 that according to Myers (1990) creates multicollinearity problems. Yet, the VIF value of 5 is within the threshold values that according to Krebs *et al.* (2012) should cause minor to considerable concerns. As there are no universally recognised rules about what values of the VIF should cause concern (Krebs *et al.* 2012), we decided to test the performance of both variables in the preliminary regression model. As they both entered the final stepwise model, T_{mean} was excluded from analysis in order to avoid any further inconsistencies, on the basis of the considerably lower importance when compared with the respective importance of T_{maxm} (Fig. 7). The GLS model parameters are presented in Table S1 of the Supplementary material.

From the OLS residual diagnostics (Fig. S4), it can be observed that although residuals were normally distributed, they were autocorrelated, therefore the regression model should be accordingly adjusted. Based on the ACF and PACF of residuals, and on diagnostics based on AIC criterion, an AR_2 model was chosen as the most suitable with which to filter residuals. The resulting model and its residual diagnostics are respectively presented in Table 4 and Fig. 8. All model diagnostics (AIC, Bayesian Information Criterion (BIC) and likelihood (Log-Lik)) are improved after the adjustment of the autocorrelated residuals, but normality of residuals is slightly biased (Fig. 8).

Discussion

Future projections anticipate a shift to a temperature-driven global fire regime in the 21st century that implies an unprecedentedly fire-prone environment where, in the future, climate will play a considerably stronger role in driving global fire trends (Pechony and Shindell 2010). Aldersley *et al.* (2011) recently concluded that in all regions, with the exception of South America, climatic parameters outweighed anthropogenic factors as drivers of wildfire burnt area. During the last decades an increase in the number and size of fires has been observed in European Mediterranean areas (Moreno *et al.* 1998; Piñol *et al.* 1998) and elsewhere (Flannigan *et al.* 2009), revealing a change in fire regime. Pausas and Fernández-Muñoz (2012) observed a major fire

Table 3. Multicollinearity tests results

Abbreviations: T_{max}, maximum air temperature, T_{maxm}, mean maximum air temperature; T_{maxa}, absolute maximum air temperature; T_{mean}, mean air temperature; p_{fir}, fire-season precipitation

Condition index	Variance decomposition proportions				
	Intercept	T_{maxm}	T_{maxa}	p_{fir}	T_{mean}
1	–	–	–	–	–
2.526	–	–	–	0.918	–
50.321	–	–	0.889	–	–
91.16	0.914	–	–	–	–
220.422	–	0.945	–	–	0.914

Variance inflation factors			
T_{maxm}	T_{maxa}	p_{fir}	T_{mean}
5.511	1.418	1.076	5.145

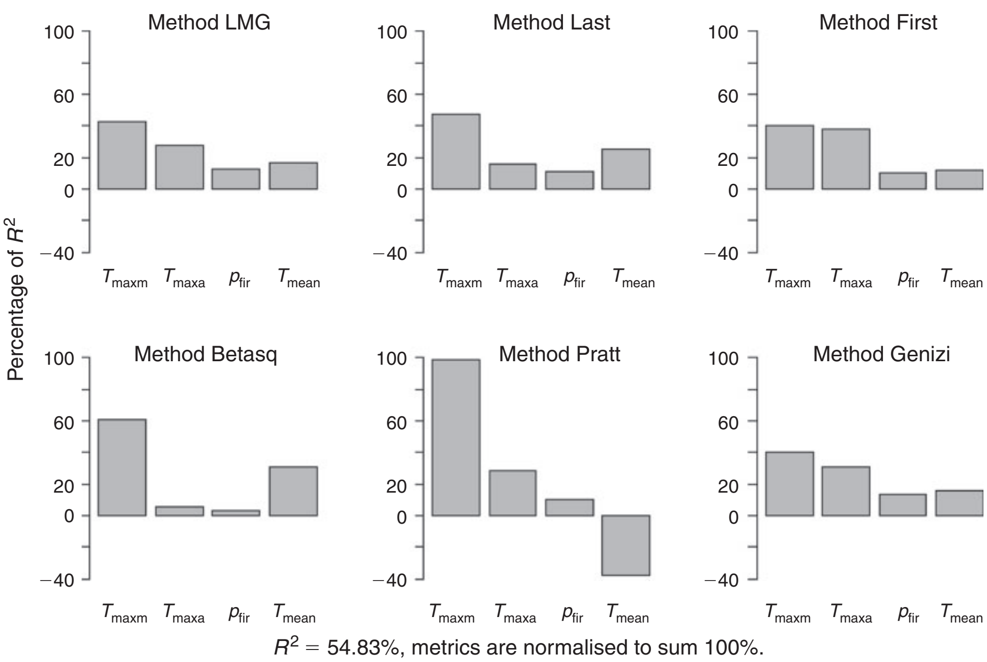

Fig. 7. Relative importance of predictors in the preliminary ordinary least-squares (OLS) regression. For details concerning the measures applied readers should refer to Grömping (2006). Abbreviations: T_{maxm}, mean maximum air temperature; T_{maxa}, absolute maximum air temperature; p_{fir}, fire-season precipitation; T_{mean}, mean air temperature.

regime shift in Spain in the 1970s as a result of the increase of fuel amount and continuity due to rural depopulation but, in contrast, the agricultural land abandonment is associated with a decrease in ignition probability in Sardinia (Ricotta *et al.* 2012). A shift in wildfire regime has been reported for Greece, consisting of a significant increasing trend in wildfire occurrence and area burnt during the last four decades (Dimitrakopoulos *et al.* 2011).

Table 4. Generalised least-squares (GLS) regression with an autoregressive moving average (ARMA) (2,0) model fitted in residuals
Abbreviations: variables as Table 3; AIC, Akaike information criterion; BIC, Bayesian information criterion; loglik, log likelihood

GLS regression with ARMA(2,0) residual fit				
Coefficients	Value	s.e.	*t*-value	*P*
(Intercept)	−4.649	3.368	−1.380	0.174
T_{max} mean	0.392	0.159	2.463	0.017
T_{max} abs	0.151	0.044	3.471	0.001
p_{fir}	−0.005	0.001	−3.280	0.002
ARMA (2,0 coefficients)				
Phi1	Phi2			
0.233989	0.367693			
Model diagnostics				
AIC	BIC	loglik		
117.0232	131.0745	−51.5116		
Standardised residuals				
Min.	Q1	Med.	Q3	Max.
−2.89303	−0.57737	0.082435	0.656807	2.117127
Residual standard error: 0.7117				

In our analysis, significant trends were observed for the number of fires and the area burnt in all three periods studied except 1974–2010. However, two periods with different fire regimes were observed; one prior to and one after 1974. The period 1974–2010 is characterised by larger fires than is the period before 1974. The observed increase in total yearly burnt area during the later period is most likely linked to increased fuel accumulation through land abandonment and afforestation of former agricultural land, as stated by Pausas and Fernández-Muñoz (2012). Based on official European fire statistics, there is a clear decreasing trend of the average fire size in five southern European countries (Portugal, Spain, France, Italy and Greece) after 1990 partly due to the improvement of fire protection services (Schmuck *et al.* 2011). This pattern is also observed in our study where after 1990 the average size showed a decreasing trend with the exception of the years 1998, 2000 and 2007, indicating among others the role that management activities and suppression strategies may have played.

Statistically significant positive trends were observed for absolute and mean air temperatures, whereas annual and temporal precipitation records presented mainly negative (though not significant) trends. Climatic changes expressed through weather extremes have been also observed recently in Greece (Founda and Giannakopoulos 2009; Tolika *et al.* 2009), and there has been a global-scale increase in mean air temperature especially in the 1970s (Nicholls *et al.* 1996). del Río *et al.* (2011) observed positive trends in mean temperature in Spain from 1961 to 2006, and a general temperature increase during all months and seasons of the year. De Luís *et al.* (2001) reported a decreasing trend in mean annual rainfall in Valencia, during the period 1961–1990, whereas for the same area Pausas (2004) reported a decreasing trend in summer rainfall although annual rainfall did not show a clear trend with time. Dimitrakopoulos

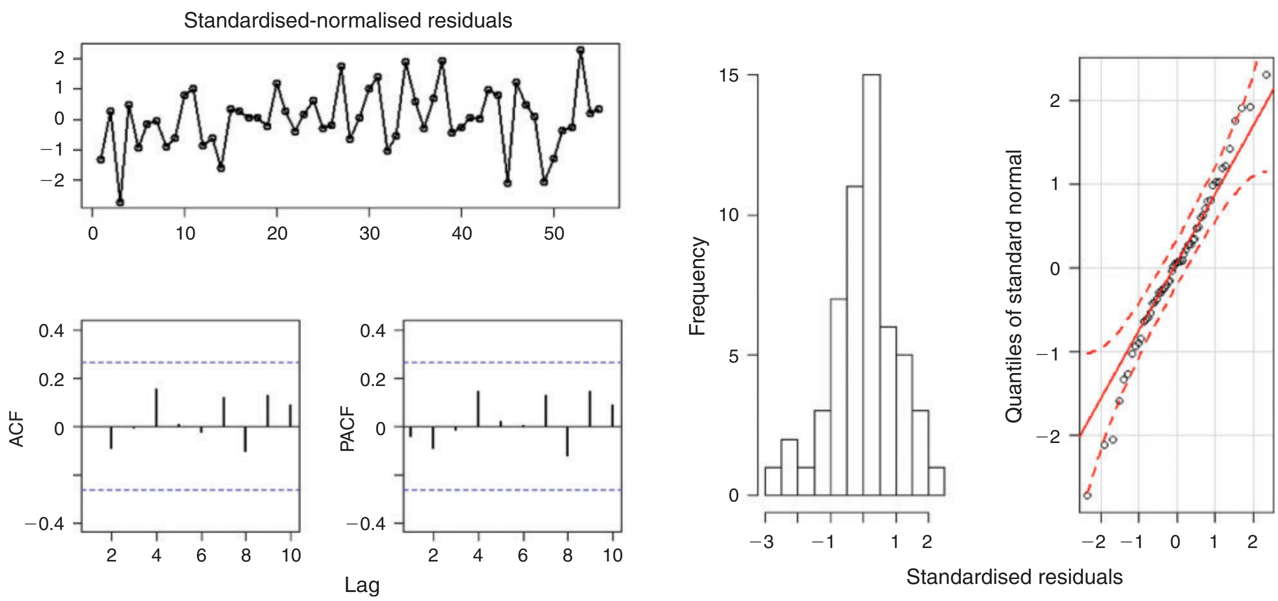

Fig. 8. Standardised-normalised regression residuals. Autocorrelation (ACF) and partial autocorrelation function (PACF) diagrams (left part) and histogram and QQplot of standardised-normalised residuals of generalised least-squares (GLS) regression with autoregressive moving average (ARMA) (2,0) fit to residuals.

et al. (2011) also found a trend in annual drought episodes in Greece from 1961 to 1997, suggesting a link with precipitation deficits during the whole year, not only during the summer months.

In the current study, autocorrelation patterns found in the number of fires and the annual total burnt area, which respectively reflected a 4- and 7-year timespan peak, occasionally matching the 4- and 7-year autocorrelation found in selected weather parameters such as precipitation and temperature. Air temperature showed a decadal pattern, which was very pronounced in regard to average temperature. This pattern might be related to the decadal cycles of solar activity (Thejll 2001; Barlyaeva *et al.* 2009). Other higher frequency structures are related to the oscillatory nature of large-scale atmospheric circulations and teleconnection patterns that affect Europe and particularly eastern Mediterranean areas, such as the North Atlantic Oscillation (NAO), El Niño–Southern Oscillation (ENSO) and the Scandinavian variability patterns (SCAND) (Hasanean 2001; Trigo *et al.* 2004; Ulbrich *et al.* 2012).

The change in autocorrelation patterns of area burnt that is observed during the period 1974–2010 (Fig. S1) when discussed alongside the historical time series of the same variable presented in Fig. 1, shows that there is also a change in the fire regime during this period. From a rather smooth pattern of area burnt where high peaks were absent and inter-annual variability is considerably low, there is a transition towards high peaks of area burnt followed by years with considerably low values of area burnt (negative autocorrelation) followed again by high values of area burnt after 7 years, indicating a possible increase in extremes.

Precipitation trends were not significant, but a positive long-term tendency was observed in the amount of spring precipitation and a negative one in the summer precipitation. Autocorrelation peaks found at 7 years in the winter, spring and fire-season precipitation, are possibly associated with the 7–8-year oscillatory mode of NAO (Kalimeris *et al.* 2012). Climatic signals in the 3.5-year band related to ENSO have been reported by many researchers. For example, Feliks *et al.* (2010) reported significant oscillatory modes at 4.3, 3.8 and 3.3 years in the precipitation of the south-eastern Mediterranean.

Various European regional studies have explored the relationship between fires and weather parameters. In Portugal fire weather (temperature, precipitation, humidity and wind) explains the majority of the variance of the area burnt and the number of fires (Carvalho *et al.* 2008). Pausas (2004) concluded that number of fires and area burnt correlate significantly with summer or fire season rainfall amount on the Iberian Peninsula, whereas Piñol *et al.* (1998) found various expressions of air temperature as the most important. Dimitrakopoulos *et al.* (2011) found a significant positive correlation between drought, wildfire occurrence and burnt area throughout Greece during the period 1961–1997.

These suggestions are supported by the correlation and regression analyses results of the present study. The mean maximum air temperature and the absolute maximum air temperature have been identified among the variables to have the highest correlation coefficients with area burnt. This is not surprising as high values of absolute maximum temperature occur in summer heat waves, triggering fire occurrence. This correlation points to the importance of these parameters and suggests they should be considered when predicting fire danger in Greece.

Concerning the precipitation variables, spring precipitation is positively associated with burnt area showing a positive lagged correlation for 3 consecutive years. Total and summer precipitation were found to have positive lagged correlations with the burnt area 2 years later, a finding similar to that of Pausas (2004) and Westerling *et al.* (2003), who observed that correlation between moisture and area burnt changes from positive 1 year before, to negative immediately before and during the fire season. This is due to the positive correlation between moisture availability in the previous year and biomass production and fuel accumulation. In contrast wet conditions during the current fire season restrict fire hazard by moistening fuels, whereas moisture extinction resulting from dry weather triggers fire activity.

These findings indicate that fire season severity is affected not only by precipitation and temperature conditions earlier in the year and during the fire season, but is also influenced by the precipitation of the previous years, particularly during the growth season. Nevertheless, it has to be pointed out that based on the results from the regression analysis, among precipitation-related variables, only fire-season precipitation at lag0 entered the regression model. This suggests that, although annually lagged precipitation totals may indeed favour fine fuel production and accumulation, it is lag0 fire-season precipitation that mainly drives fire spread through directly controlling fuel moisture.

The GLS regression using mean and absolute maximum air temperature and fire-season precipitation as predictors of the area burnt, showed that annual or seasonal weather parameters indeed explain a large proportion of total variation. Similar results are also reported for Canadian peatlands where variation in area burnt is largely explained by maximum temperature and moisture variables (Turetsky *et al.* 2004). Additionally, in some regions in Spain the maximum air temperature generally outperformed precipitation variables in explaining burnt area variation and, similarly to our results, mean temperature only played a minor role (Vázquez and Moreno 1993).

Pausas and Fernández-Muñoz (2012) found poor correlations between climatic conditions and fire activity before the 1970s whereas a strong relationship was observed in post-1970s fires, suggesting that fires are currently less fuel limited and more drought driven now than they were before the 1970s. These findings are interesting in light of qualitative findings in the current research in relation to the correlation between area burnt and weather parameters when different periods are considered. There are strong indications of an underlying relationship between fires and socioeconomic factors (Koutsias *et al.* 2010) and area burnt, that besides actual and past weather, depends also on efficiency of fuel management and fire suppression (Cary *et al.* 2009), on various landscape parameters (Viedma *et al.* 2009) and on other human activities (Zumbrunnen *et al.* 2012). These variables weaken the correlation strength between fire- and weather-related variables (Vázquez and Moreno 1993) and at least partly explain the variations that were also detected in the present study when different periods were considered.

Conclusions

Climatic data from the oldest meteorological station in Greece were combined with historical forest fire data to investigate long-term relationships (1894–2010) between forest fire statistics and meteorological observations. We sought to find temporal patterns and trends in these historical records and to identify any bivariate relationships between meteorological parameters and fire occurrence at a national level.

The findings of this study suggest that weather is an important factor that controls to some extent fire occurrence in Greece. Fire regime in the Mediterranean is influenced by factors beyond those related directly to weather conditions (e.g. socio-economic, LULC, anthropogenic pressures and intensive human influences), however climatic and weather conditions have a profound effect on fire occurrence over time. The relationships identified could be used in short-term predictive models of fire risk as well as inputs in long-term future fire risk models under climatic change scenarios.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Program (FP7/2007-2013) under grant agreement number 243888 (FUME project). We acknowledge the National Observatory of Athens, Hellenic Forest Service and Hellenic Fire Brigade for providing data used in this study. The authors also thank the editors and reviewers of the *International Journal of Wildland Fire* for their valuable comments that significantly improved the quality of the manuscript.

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