CLIMATE WARMING, WILDFIRE HAZARD, AND WILDFIRE OCCURRENCE IN COASTAL EASTERN SPAIN

JOSEP PIÑOL, JAUME TERRADAS and FRANCISCO LLORET
Centre de Recerca Ecològica i Aplicacions Forestals, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

Abstract. A climatic series (1941 to 1994) from a Mediterranean locality of NE Spain was used to calculate two wildfire hazard indices based on daily meteorological data. Both fire hazard indices increased over this period, as a consequence of increasing mean daily maximum temperature and decreasing minimum daily relative humidity. These trends were observed in both mean values of the indices and in the number of very high risk days. Annual data on the number of wildfires and burned area also show an increase from 1968 to 1994, and are significantly correlated with both fire hazard indices. Although other non-meteorological causes (e.g., human activities, fuel accumulation) have likely contributed to the observed increase of wildfires, an effect of climatic warming on wildfire occurrence is supported by this relationship.

1. Introduction

One of the major environmental concerns in Mediterranean areas is the occurrence of devastating summer forest wildfires. The 1994 fire season was especially dramatic in Spain. More than 430,000 ha of forest, shrubland, and grassland burned in 1994 in the entire country, causing 31 human casualties (Vélez, 1995, 1996). The number of wildfires was not very different from that observed in preceding years, but the area burned by several of them was very large, especially those that started around the 4th of July. During this week, there were several large wildfires all along the Mediterranean coast of Spain, from Barcelona to Andalucía. The impact of 1994 wildfires on the Spanish public and scientific community was comparable to the impact of the Yellowstone 1988 wildfires on American society (Rothermel et al., 1994).

The relationship between meteorological conditions and fire occurrence is well known (Chandler et al., 1983). Forest fires tend to be concentrated in summer months when temperature is high and air humidity and fuel moisture are low. In this century the climate has changed by an increase of mean temperature at a global scale (Houghton et al., 1996). Because this increase has been especially noticeable since the 1970s (Nicholls et al., 1996), it is possible to examine whether the changing climate has already affected the frequency and magnitude of forest fires. One way to analyze the relationship between fire occurrence and climate is by using meteorological fire hazard indices. The main problem in using these indices is that they must be applied to daily or even shorter periods, and that atmospheric relative humidity and wind speed data are normally necessary. Such detailed data are available in few places in Spain, especially if we require long records.

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Several authors have already addressed the possible impacts of global warming on wildland fire using fire behavior models and GCM predictions of future climate (Flannigan and van Wagner, 1990; Torn and Fried, 1992; Davis and Michaelsen, 1995). Few have tried to analyze whether the fire history of a region matches instrumentally observed variations in climate, as Balling et al. (1992a,b) did at Yellowstone National Park after the devastating 1988 fire season. A number of other workers have compared historical, tree-ring, lake-sediment charcoal, and other proxy records of fire with climatic proxy records over longer time periods (Clark, 1988; Meyer et al., 1992; Swetnam and Betancourt, 1990; Swetnam, 1993).

The objectives of this study are (1) to examine if the meteorological fire hazard has already changed in this century by using the longest available meteorological record in the Mediterranean coast of Spain; and (2) to compare the incidence of forest fires with two meteorological fire hazard indices. We are aware that in a correlational approach to the study of fire history and climate there is a fundamental difficulty of accounting for simultaneous changes in many other interrelated components of fire regime, such as the abandonment of agriculture and pasture lands in the region over the period of record. This land use change has been more important in the southern part of the study area (between 0% and 15% of new forests and shrublands) than in the more humid and productive northern part (with virtually no change). Nevertheless, considering that the wildfire-weather relationship is well established, the analysis of a single component of the total fire hazard, the meteorological fire hazard, is still meaningful.

2. Data and Methods

2.1. STUDY AREA

In this paper we analyze the strip of Mediterranean coastal land between the provinces of Barcelona and València (Figure 1). This area (31,358 km^2) comprises 4 administrative units: the provinces of Barcelona, Tarragona, Castelló de la Plana, and València. The climate of most of the area is Mediterranean, with mild winters and warm and dry summers. From north to south there is a gradient of increasing aridity, as a consequence of increase of temperature (and accordingly, of potential evapotranspiration), and decrease of precipitation (Table I). The more frequent vegetation types in the region, and also the more prone to wildfires, are forests or woodlands dominated by *Pinus halepensis*. The forest understory is highly variable, but it is usually well developed and rich in helio-xerophytic species such as *Quercus coccifera*, *Rosmarinus officinalis*, and *Erica multiflora*, on calcareous soils, and *Erica arborea*, and *Cistus* spp., on neutral or acidic soils. According to the NFFL fuel model classification (Rothermel, 1983), most of the vegetation in the study area corresponds to the very flammable shrub models 4, 5, 6 and 7.

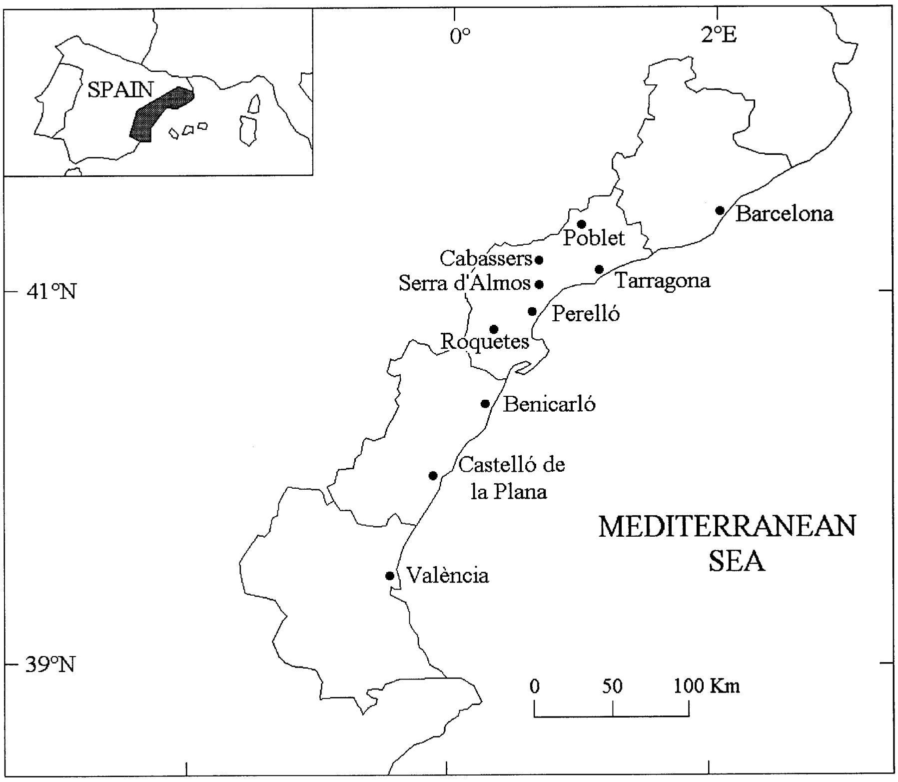

Figure 1. Geographical location of the study area.

Table I

Mean annual temperature and precipitation at several locations on the Mediterranean coast of Spain. Localities are ordered from north to south (data taken from Riba et al., 1980)

Locality	Mean annual prec. (mm)	Mean annual temp. (°C)	Latitude	Altitude (m a.s.l.)	Distance to the sea (km)
Barcelona (Obs. Fabra)	598	16.5	41°25′ N	410	7
Tarragona	476	15.8	41°08′ N	12	0.5
Roquetes	549	16.6	40°49′ N	55	25
Benicarló	555	16.6	40°25′ N	11	1
Castelló de la Plana	443	17.2	39°59′ N	47	5
València	434	17.1	39°27′ N	13	5

2.2. FOREST FIRES DATA BASE

Detailed statistics for forest fires in Spain are available since 1968. There were very few gaps in the data base: 1979 for Tarragona and València, and 1994 for Castelló de la Plana. To fill these gaps, the number of fires and the burned area for these years and provinces were estimated by linear regression from the average of the provinces located to the north and to the south of the province without data.

Forest fires occur throughout the year, but in the summer months they are much more frequent and much larger. In this paper we will deal with the main fire season: June to September. In the paper the terms ‘summer’ and ‘fire season’ are used as synonyms.

2.3. METEOROLOGICAL DATA

The present study is based largely on the analysis of the meteorological record for the rural station of Roquetes (Figure 1). Roquetes has the longest (1910–) and most continuous meteorological record of the area, including daily maximum and minimum temperatures, precipitation, maximum wind velocity, and minimum relative humidity (this last variable only since 1941 to the present). Another useful meteorological station is located in Barcelona (Observatori Fabra). Its record started in 1914, but because of its location, the last part of the record (since the 1950s or 1960s) is likely unsuitable for long term comparisons due to the urban effect of Barcelona. Nevertheless, we used data from the Observatori Fabra and from some other stations in the area with much shorter records to check the validity of the temporal trends observed at Roquetes.

Potential evapotranspiration (E_T) was estimated using the Samani-Hargreaves method (Samani and Hargreaves, 1985, quoted in MacKenney and Rosenberg, 1993). This method was chosen because it produces reasonable estimates of E_T compared with the state-of-the-art Penman-Monteith method (MacKenney and Rosenberg, 1993), but with fewer data requirements. This method calculates daily E_T (mm) as a function of the daily extraterrestrial radiation (R_a, in mm H_2O equivalent), the mean daily temperature (tF, in degrees Fahrenheit), and the difference between minimum and maximum daily temperature (tD, in degrees Fahrenheit):

$$E_T = 0.00094 * R_a * tF * tD^{1/2}$$

where R_a was computed by the method described by Allen et al. (1989).

2.4. FIRE HAZARD INDICES

Two different fire hazard indices were calculated using the meteorological data of Roquetes. The first index is an estimation of the flammability of the fine dead fuel and is obtained from tabulated data on relative humidity and temperature (ICONA, 1988). Combined with wind speed data it is routinely used by local agencies to forecast fire risk in the area. In this paper we only use the part of the index that gives the flammability of the fine dead fuel.

The second index ($\mathrm{I87_{mod}}$) is a modification of the I87 index of Carrega (1991). The modifications do not affect the original purpose of the index and are intended to improve estimation of the soil water reserve. It is calculated by:

$$\mathrm{I87_{mod}} = ((t * v)/(r * r_{\mathrm{sup}} * h)) * C$$

where t is air temperature in degrees Celsius, v is wind speed in m s^{-1}, r is the water reserve of the soil (saturated at 150 mm), r_{sup} is the reserve of the superficial layer of the soil (saturated at 10 mm), h is the air relative humidity (in %), and C is a phenological coefficient corresponding to 100 in autumn and spring when plant activity is high and to 200 in summer and winter, periods of reduced activity. Carrega (1991) proposes a method to estimate the variation in the reserves of the soil (r and r_{sup}) following an exponential decrease dependent on the accumulated potential evapotranspiration calculated by the method of Thornthwaite. We modified this index (1) by computing E_0 by the method of Samani-Hargreaves (1985) rather than by the method of Thornthwaite, and (2) by the way in which the soil water stores are depleted: we used a simple two-bucket soil model, with water extraction proportional to the soil water content and E_0 for the main soil reserve, and at the potential rate for the superficial reserve. The index was calculated by using daily values of maximum temperature, minimum relative humidity, and maximum wind velocity.

According to Carrega (1991), a given day is of very high fire risk if the $I87_{mod}$ index was greater than 200. An ICONA index value of 80% was chosen arbitrarily as a threshold for very high risk days.

The main difference between these two meteorological indices is that the ICONA index measures rapid changes in the desiccating potential of the atmosphere, whereas the $I87_{mod}$ index also takes into account the effect of decreased soil water availability. The ICONA index is an estimate of fine dead fuel moisture, whereas the $I87_{mod}$ index would be more closely related to fine live fuel moisture. As both indices involve relative humidity, they could be only calculated for the period 1941–1994.

3. Results

3.1. NUMBER OF FOREST FIRES AND BURNED AREA

Between 1968 and 1994, 16,776 vegetation fires that burned a total of 738,306 ha were recorded in the study area. Most (67%) of these fires started during the fire season (June to September), and they accounted for 85% of the total burned area. As is common with forest fires (Strauss et al., 1989; Vázquez and Moreno, 1995), most of the burned area was caused by a very small number of fires: during the fire season there were only 144 forest fires (1.3%) larger than 1,000 ha that burned 487,793 ha (78% of the total area burned).

The number of summer forest fires increased significantly between 1968 and 1994 in the eastern coast of Spain (Figure 2a) at a rate of 21 forest fires per year ($r = 0.77$, $p < 0.001$). Three years had a much lower number of fires compared with the preceding and following years: 1972, 1977 and 1992. The area burned did not increase steadily; there were years when the burned area was much higher

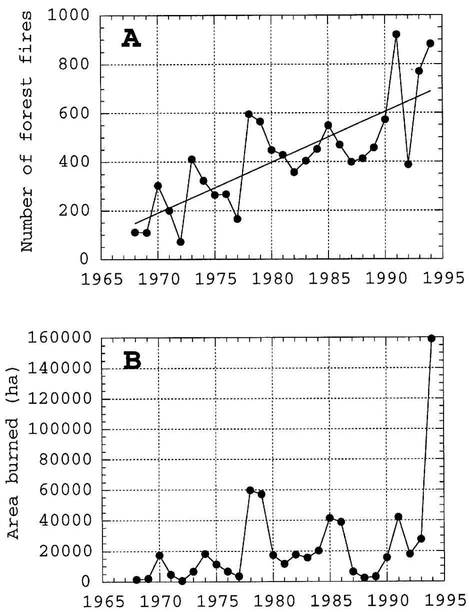

Figure 2. Number of forest fires (A) and area burned (B) during the fire season (June to September) in the provinces of Barcelona, Tarragona, Castelló de la Plana and València in the period 1968–1994.

than during the 'normal' years. The largest fire years were 1978, 1979, 1985, 1986, 1991, and, above all, 1994 (Figure 2b). When whole-year data were considered, the trends in the number of forest fires and in the area burned was similar to that of the summer period (data not shown).

3.2. METEOROLOGICAL RECORD OF ROQUETES

Mean annual temperature increased 0.10 °C per decade over the period 1910–1994 ($r = 0.49$, $p < 0.001$) as a consequence of an increase of mean daily maximum temperature ($r = 0.67$, $p < 0.001$), but not of mean daily minimum temperature (Figure 3). Estimated annual potential evapotranspiration (E_0) increased 13 mm per decade ($r = 0.78$, $p < 0.001$), but annual precipitation did not change significantly (Figure 3). As a consequence, annual water deficit ($E_0 - P$) increased. The rate of increase of the mean annual temperature was considerably higher (0.30 °C per decade for annual daily mean, maximum and minimum temperature) if only the years with wildfire data were considered (1968–1994).

Maximum, minimum and mean temperatures, precipitation, and potential evapotranspiration for the fire season (June to September) showed the same temporal trends observed in the annual data. The minimum daily relative humidity in these months decreased 0.8% per decade over the period 1941–1994 ($r = -0.48$, $p < 0.001$; Figure 4). In short, climate at Roquetes has become warmer and drier over the last 85 years.

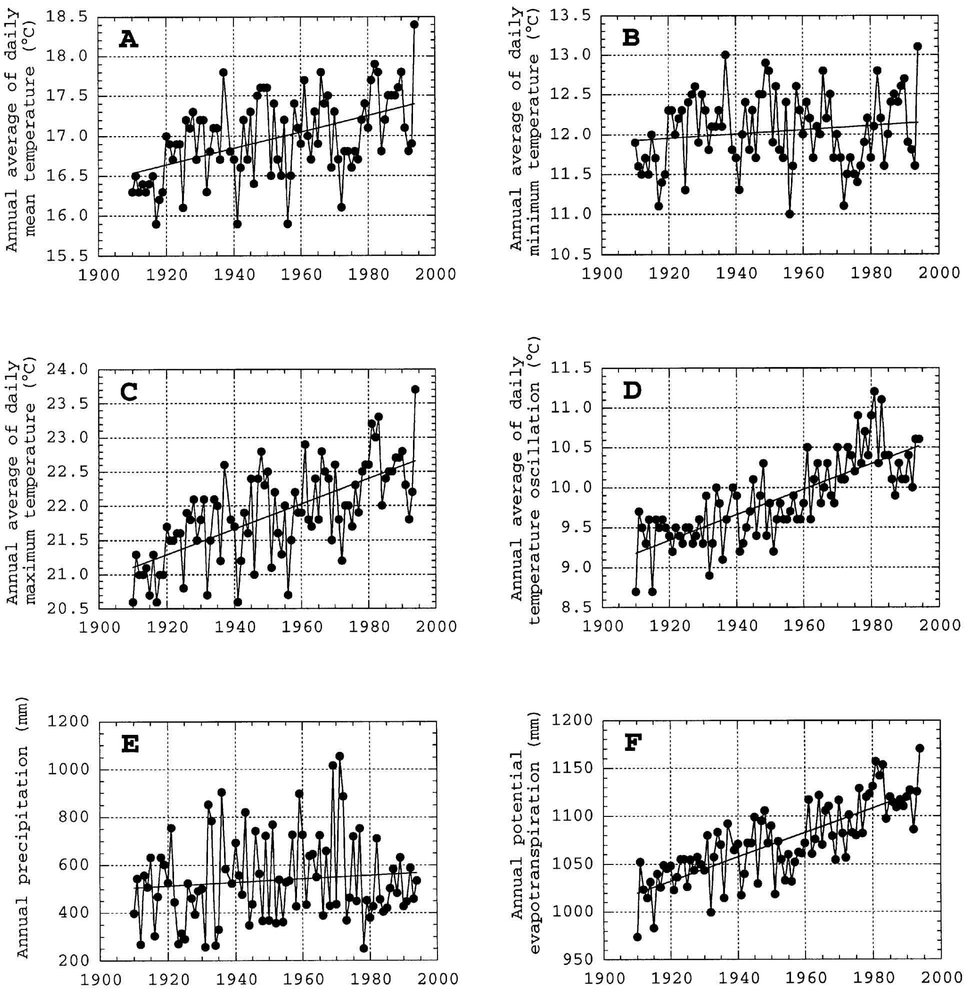

Figure 3. Annual mean values of daily mean temperature (A), daily minimum temperature (B), daily maximum temperature (C), daily temperature range (D), annual precipitation (E), and annual potential evapotranspiration (F) at the meteorological station of Roquetes from 1910 to 1994. The year 1938 was missing from the temperature records.

Mean values of both fire hazard indices during the summer months increased over the period 1941–1994. Nevertheless, most of the wildfire impact occurs during extreme dry periods, rather than from effectively drier average climate. Thus, more important than the mean value of a hazard index is the number of days that a pre-determined, high value of the index is exceeded. Despite very high interannual variability, the number of such very high fire hazard days (as defined in the Methods section) per summer did also increase significantly during the period 1941–1994 at a rate of 1.6 days per decade for the ICONA index ($r = 0.44$, $p < 0.001$,

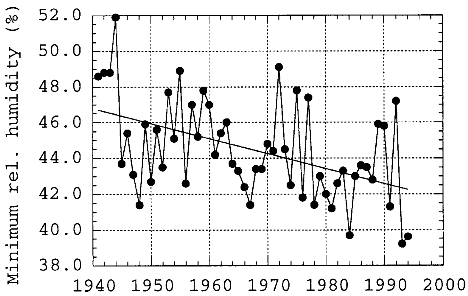

Figure 4. Mean value of the daily minimum relative humidity during the months of June to September at Roquetes for the period 1941–1994.

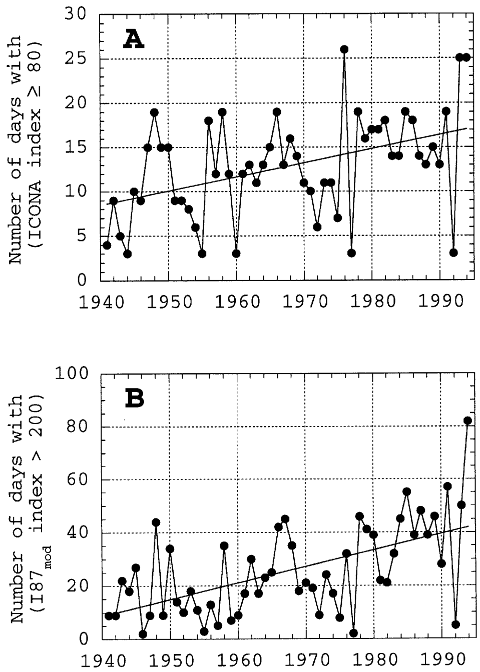

Figure 5. Number of days in the months of June to September that the ICONA fire risk index value of 80% (A) and the $I87_{mod}$ index value of 200 (B) were exceeded in the period 1941–1994.

Figure 5a), and at 6.2 days per decade for the $I87_{mod}$ index ($r = 0.57$, $p < 0.001$, Figure 5b).

There is good agreement between the temporal trend of the annual mean temperature observed at Roquetes and that observed at some other meteorological stations of the region with shorter records (Table II).

Table II

Linear correlation of the annual mean temperature measured at the meteorological station of Roquetes with the mean annual temperature of some other stations of the region

Meteor. station	r	n of years	Latitude	Elevation (m a.s.l.)	Distance to the sea (km)
Cabassers	0.92	23	41°15′ N	357	32
Perelló	0.91	22	40°53′ N	142	5
Serra d'Almos	0.84	19	41°05′ N	226	17
Monestry of Poblet	0.89	16	41°23′ N	480	33
Barcelona (Obs. Fabra)	0.85	80	41°25′ N	410	7

3.3. RELATIONSHIP BETWEEN FOREST FIRES AND FIRE HAZARD INDICES

The number of days that a pre-determined value of both fire hazard indices was exceeded is positively and linearly correlated with the number of forest fires that occur during the fire season ($r = 0.59$, $p < 0.01$, and $r = 0.78$, $p < 0.001$, for the ICONA and $I87_{mod}$ indices, respectively; Figure 6a,b). The relationship between the number of very high risk days per fire season and the area burned is also significant, but exponential rather than linear ($r = 0.53$, $p < 0.01$, and $r = 0.88$, $p < 0.001$, for the ICONA and for the $I87_{mod}$ indices, respectively; Figure 6c,d). The $I87_{mod}$ index was much better correlated than the ICONA index with both the number of fires and the area burned.

As 1994 was anomalous with respect to area burned, the above correlation coefficients were also calculated without considering this year. Results were essentially identical regarding the number of fires vs. fire hazard indices. Correlation coefficients between area burned and the $I87_{mod}$ fire hazard index was still significant ($r = 0.55$, $p < 0.01$) but not between area burned and the ICONA index ($r = 0.34$, $p > 0.05$). Considering these results, it appears that the total number of wildfires is more strongly associated with the meteorological variables than is the area burned.

4. Discussion

Analysis of the wildfire data base showed that both the number of fires and the area burned increased between 1968 and 1994 in the study area, despite an increased fire suppression effort in later years. The summer of 1994 was the worst fire season since 1968, and we found no reference to wildfires of such magnitude in 20th century administrative records. References from previous periods are only indirect, and do not allow an estimation of frequency and/or magnitude similar to the current statistical records. For instance, Riera-Mora and Esteban-Amat (1994) studied charcoal in sediments dated from ca. 6870 to ca. 250 B.P. from ancient marshes and deltaic plains in the Central Catalan coast. They found an increase in

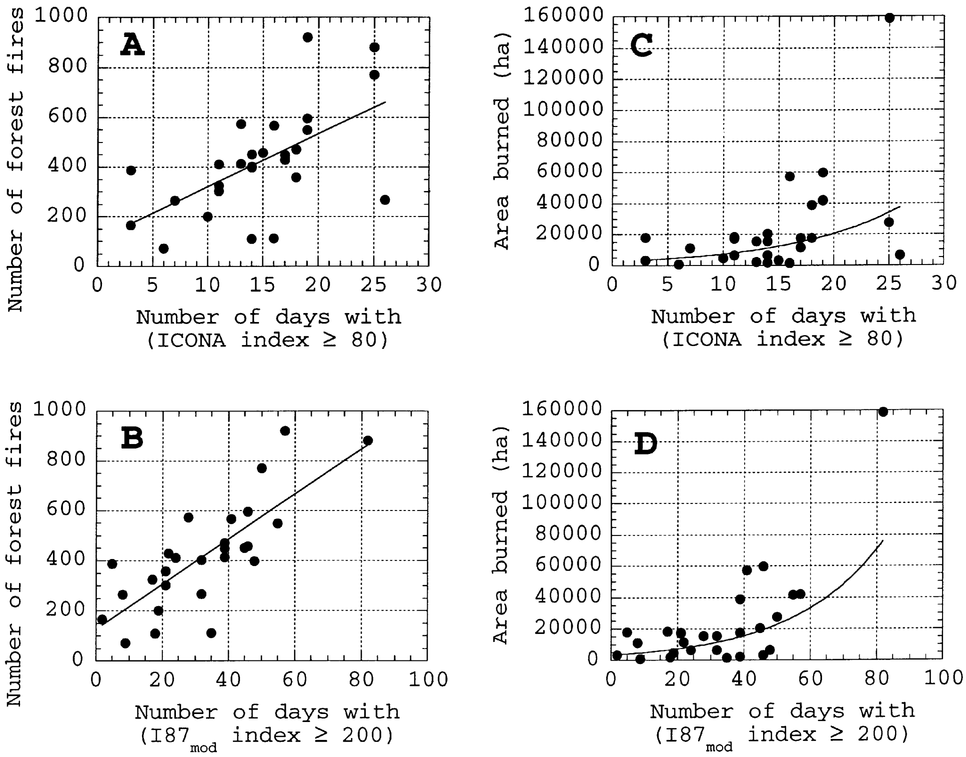

Figure 6. Relationship of the number of days that a pre-determined very high value of fire hazard index were exceeded with the number of wildfires during the fire season (A: ICONA index, B: $I87_{mod}$ index), and with the area burned during the fire season (C: ICONA index, D: $I87_{mod}$ index).

charcoal concentration associated to fires since ca. 2400 B.P. with relative maxima, probably associated to human activity, between ca. 1500 and ca. 850 B.P., and again at the end of the record (ca. 250 B.P.). There are also occasional references to important wildfires in historical documents (de Torres, 1989) and in the non-scientific literature (Ruyra, 1928).

Analysis of the meteorological record for Roquetes showed an increase in temperature and aridity between 1910 and 1994. Comparison of annual temperatures of Roquetes with shorter meteorological records in the study area confirmed the regional consistency of the temperature trend observed at Roquetes. The increase in aridity did not come from a decrease in the annual rainfall but from an increase of mean temperature and diurnal temperature range, which resulted in a higher estimated potential evapotranspiration. The rate of temperature increase observed at Roquetes during the period 1968–1994 was slightly greater than that reported for the global surface temperature (0.2–0.4 °C for the last 40 years; Nicholls et al., 1996). The increase came from increased maximum but not minimum temperatures (1910–1994 period) or from the increase of both maximum and minimum temperatures (1968–1994 period). This result contrasts with that generally reported at the global scale, in which minimum temperature increased at a higher rate than maximum temperature, thus resulting in a reduced diurnal temperature range (Nicholls et al., 1996).

The change in the meteorological variables resulted in an increase in the two fire hazard indices for the summer months (June to September) over the period 1941–1994. The increase occurs both in the mean values of the indices and in the number of very high fire hazard days. These results are similar to those obtained at Yellowstone using a multivariate approach (Balling et al., 1992a) or a drought index (Balling et al., 1992b) instead of fire hazard indices.

We also found a significant relationship between the number of very high fire risk days and the number and area of wildfires. This result could lead us to conclude that the number and area of forest fires increased because of the changing climate. Nevertheless, clearly we cannot make such an assertion simply on the basis of meteorological data alone. The incidence of wildfires depends on many factors, and only some of them are meteorological.

Among other factors affecting fire incidence, human activity is of primary importance. Humans are the main cause of fire initiation in Spain, where only around 10% of the fires are lightning-caused (Vázquez and Moreno, 1995). Humans have also had the opposite influence, through fire suppression. In Spain, human causes of ignition and fire suppression efforts have both increased in the period 1968–1994, whereas rural activities have decreased. Land-use change in eastern Spain during that period has included both the abandonment of low-productivity crops and grazing lands that have been replaced by open forests or woodlands with a dense understory, and the abandonment of previously exploited, low productivity-forests. In consequence, forest continuity and biomass increased. These changes enhanced the likelihood of fire occurrence and severity. It is difficult to obtain precise figures on the number and distribution of ignition causes or in land-use modifications. Clearly, these changes confound the relationship between meteorological fire hazard and fire activity.

Despite the above uncertainties, we maintain that the drier and warmer climate has likely contributed to increased fire activity in Spain since 1968. The observed trends in temperature are similar to that predicted at the global scale (Kattenberg et al., 1996). Regional GCM simulations up to year 2100 for Southern Europe predict summer temperature increase, but there is no agreement on predicted future precipitation (Kattenberg et al., 1996). The latest IPCC report on potential impacts of climate change also predicts an increase of wildfire activity in tropical, boreal, temperate, and Mediterranean forests in a climate forced by a doubled atmospheric carbon dioxide (Kirschbaum and Fischlin, 1996). If observed trends continue and the above prediction is realized, the number of days of very high fire risk will continue to increase in the Mediterranean area, and catastrophic wildfires like those of 1994 are likely to occur more frequently. Fire prevention and fire-fighting policies should be made with the possibility of worsening conditions clearly in mind.

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