An Objective Forecasting Model for the Daily Outbreak of Forest Fires Based on Meteorological Considerations

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ABSTRACT

Daily fire risk (DFR) is a forecasting index defined on the basis of two meteorological parameters. Such parameters are associated with the local atmospheric column: dry stability e in 850–700-hPa layer and saturation deficit D in 850-hPa level. In an earlier study, and from data collected over 10 years, a categorization of four type days based on DFR was established. In this way, from evaluation of e and D at 0000 UTC for each particular day, the associated type day was deduced. Consequently, it is possible to know whether that day had either very high, high, low, or very low fire activity. With this technique it is not possible to forecast a numerical value for the number of fires, however.

In this paper a model for estimating the outbreak of fires is presented. On the basis of an autoregressive process, AR(2), it is possible to obtain the predicted number of fires (PNF) during a day d as PNF(d) = F[TD(d), RNF($d-1$), RNF($d-2$)], where TD(d) is the type day according to the categorization established on the basis of e and D (deduced from rawinsoundings at 0000 UTC) and RNF($d-1$) and RNF($d-2$) are the numbers of fires registered over the area during two previous days.

In contrast to other papers in the literature, all fires are considered. No limitations are placed on the burned area or other measures of fire activity. Several statistical computations confirm the validity of this model.

1. Introduction

Forest fires are a considerable problem in the Mediterranean and Atlantic regions of Europe. Particularly, Galicia (northwest Spain) may be considered as the area that presents the highest daily values in the number of fires registered. In summer, especially during September, more than 80 fires per day is a relatively typical number of fire outbreaks.

Galicia is located in the northwest of the Iberian Peninsula (Fig. 1) and, from a climatic point of view, it is strongly influenced by the Atlantic Ocean. In general, the atmospheric circulation is characterized by southwest to west-northwest winds, especially in autumn and winter. In summer, this general tendency may be interrupted and east to south winds may appear. From a synoptic point of view, these winds are associated with an anticyclonic domain over the Mediterranean Sea. As a result, high temperatures and strong drying are produced over Galicia. For this reason, July, August, and September are the months with the highest incidence of forest fires.

In the bibliography, the predictive indexes as proposed by Nesterov (1939), Palmieri and Cozzi (1983), and Haines (1988) are well known. In each case, these authors use different meteorological parameters and, from empirical expressions, they obtain predictions in terms of qualitative categories for the meteorological risk. The validity of these indices is based on statistical computations and, in this sense, several restrictions are established; for example, only major fires are considered.

Others, such as Brotak and Reifsnyder (1977) and Brotak (1980), analyze this problem exclusively from a synoptic point of view. Particular temporal sequences at middle levels and/or the surface are synoptic indices for the possible ignition of fires.

According to this method, the meteorological indices allow the calculation of the possible daily fire activity but an estimation of the number of fire outbreaks may not be obtained. This is precisely the problem we analyze in this paper.

In a previous study (Garcia Diez and Salazar 1991) DFR (daily fire risk) appears as an operative index that allows an estimation at 0000 UTC of whether a day has either very high, high, low, or very low activity. In section 2 this methodology is explained in comparison to other well-known models. In section 3 we de-

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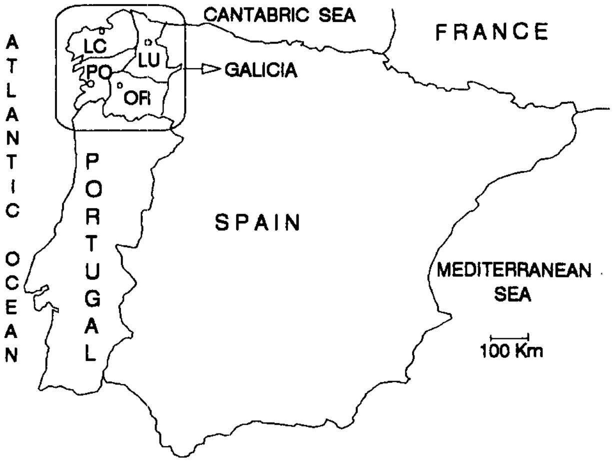

FIG. 1. Galicia (northwest Spain) includes the following districts: La Coruña (LC) (radiosonde station), Lugo (LU), Orense (OR), and Pontevedra (PO).

velop a quantitative method to obtain (each day at 0000 UTC) the number of predicted fires. In order to establish the validity of the model, we describe in section four several statistical computations.

2. Qualitative index (DFR)

DFR is defined using a categorization established on the basis of (e, D) values. The first component (e) indicates the stability in the local atmospheric column. To eliminate the orographic effects, only the 850–700-hPa pressure layer is considered. Consequently, e is given by

$$e = S_{700} - S_{850}, \tag{1}$$

where

$$S = c_pT + gz. \tag{2}$$

The dry static energy or Montgomery's potential is denoted by S (Montgomery 1936). Several properties of S have been described in Yanai and Chu (1973), Arakawa and Schubert (1974), and Rivas and Garcia (1993). In particular, $\partial S/\partial p$ is a stability index; concretely for the 850–700-hPa layer it can be approached by:

$$\frac{\partial S}{\partial p} \approx \frac{S_{700} - S_{850}}{700 - 850} \approx -\frac{e}{150}. \tag{3}$$

Since $\partial S/\partial p < 0$ imply stability, it is clear that high positive values of e are associated with strong stability.

On the other hand, D is given by:

$$D = h^*_{850} - h_{850}, \tag{4}$$

where

$$h = c_pT + gz + Lq,$$

$$h^* = c_pT + gz + Lq^*, \tag{5}$$

in which T, Z, q, and q^* are the absolute temperature (K), geopotential altitude (m), specific humidity (kg kg^{-1}), saturated specific humidity (kg kg^{-1}) and c_p, g, and L are the pressure-constant specific heat (dry air), acceleration due to gravity, and condensation latent heat of water vapor.

As seen in (4), D indicates the saturation deficit in dimensions of energy. Thus, high D values imply low water vapor content in the 850-hPa pressure level.

From daily rawindsonde measurements at 0000 UTC T, z, and q can be obtained and immediately q^* can be deduced. Consequently, the (e, D) is fixed a few minutes later. For operative reasons e and D are expressed in kilojoules per kilogram.

In previous papers (Garcia Diez and Salazar 1991; Garcia Diez et al. 1993), several statistical considerations of (e, D) in Galicia, Spain, were described. In particular, the average values of e and D for July, August, and September on a 5-yr dataset are $e = 6.7$ kJ kg^{-1} and $D = 11.8$ kJ kg^{-1}. For this reason, an (e, D) plane is considered in which the $e = 6$ and $D = 12$ kJ kg^{-1} straight lines are plotted (Fig. 2). Each particular day is plotted on the (e, D) plane as a function of its corresponding (e, D) values. A categorization of type days may be established as given in Table 1.

From a physical point of view, high D values imply low water vapor content and consequently high evaporation, which is associated with high fire risk. The direct relationship between the D value and the number of fire outbreaks has been statistically established (Garcia Diez and Salazar 1991). This conclusion is also presented by authors such as Haines (1988) and others. Specifically, Haines (1988) uses $B = (T - T_d)_{850}$ as an index for the water vapor content, where T and T_d are the temperature and the dewpoint temperature

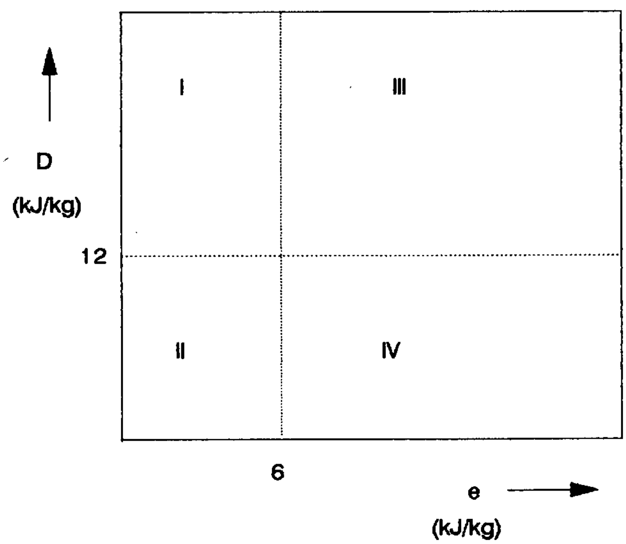

FIG. 2. Diagram to establish the type day according (e, D) value at 0000 UTC. For each day (one point) RNF may be plotted. For each month, season, or year DFR is obtained and archived.

TABLE 1. Categorization of type days.

Type day	e (kJ kg^{-1})	D (kJ kg^{-1})
I	$\leqslant 6$	$\geqslant 12$
II	$\leqslant 6$	<12
III	>6	$\geqslant 12$
IV	>6	<12

in the 850-hPa pressure level. Evidently, B and D possess a strong correlation although, in our opinion, D is physically more precise.

On the other hand, e has a contradictory influence on the number of fire outbreaks. Low e values (low stability) may be interpreted, in a first approximation, as a propitious condition for fire ignition. However, this interpretation is not correct.

Low e values imply a high number of fires only when coupled with high D values ($D > 12$ kJ kg^{-1} for example). On the other hand, if D has a low value (<12 kJ kg^{-1}), low e values imply low values in the number of fires.

These conclusions were obtained in a previous study (Garcia Diez et al. 1993) on the basis of statistical considerations. From several data taken during 1981–85 (July, August, and September examined separately for each year; July, August, and September examined together for each year; and global dataset), daily fire risk was defined as:

$$\mathrm{DFR}_i = \left(\frac{\text{number of fires}}{\text{number of days}}\right)_i, \quad i = (\mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV}). \quad (6)$$

In each case it was found that $\mathrm{DFR_I} > \mathrm{DFR_{III}} > \mathrm{DFR_{IV}} > \mathrm{DFR_{II}}$. In other words, the type of day that presents the highest fire risk is type I, that is, the day that presents low stability e and high saturation deficit D. The second type of day with highest chance of fire activity is the type III day which is characterized by high stability e and high saturation deficit D. The third type day of fire activity is type IV, which has high stability e and low saturation deficit D. Finally, type II, low stability e and low saturation deficit D, is associated with the lowest fire activity. On the basis of these results a qualitative index may be established: a few minutes after 0000 UTC on a particular day, the (e, D) is known and the corresponding type of day is assigned. Consequently, the fire activity will be "very high" (I), "high" (III), "low" (IV), or "very low" (II) according to the type of day established.

In order to confirm this qualitative method, new datasets (1986–91) are presented and analyzed in section 4.

Since this qualitative index is considered exclusively on a day-to-day meteorological scale ignoring the past weather, several important issues should be analyzed in detail.

From a physical point of view, fire occurrence is not a weather cause–effect problem. The meteorological conditions are not the direct causes of forest fires [only 3%–8% of total forest fires in Galicia were due to lightning (Vélez 1988)]. More than 50% are due to anthropogenic causes (especially arson).

Strictly speaking, meteorological conditions must be considered as a catalysis effect. Consequently, a

TABLE 2. Average monthly values in the correlations province to province of registered number of fires per day (1981–91).

Month	Province	La Coruña	Lugo	Orense	Pontevedra
July	La Coruña	1.0	—	—	—
	Lugo	0.37	1.0	—	—
	Orsene	0.46	0.38	1.0	—
	Pontevedra	0.88	0.44	0.58	1.0
August	La Coruña	1.0	—	—	—
	Lugo	0.37	1.0	—	—
	Orense	0.48	0.38	1.0	—
	Pontevedra	0.88	0.44	0.56	1.0
September	La Coruña	1.0	—	—	—
	Lugo	0.64	1.0	—	—
	Orense	0.80	0.78	1.0	—
	Pontevedra	0.75	0.65	0.52	1.0

TABLE 3. PNF(d)–RNF(d) regression output

Year (season)	r^2	Slope	Intercept	Stand error
1986 (July, August, September)	0.64	0.8	5.7	0.068
1987 (July, August, September)	0.60	0.7	14.9	0.061
1989 (July, August, September)	0.55	0.6	19.1	0.071
1990 (July, August, September)	0.70	0.8	7.8	0.065
1991 (July, August, September)	0.60	0.7	5.8	0.065
1985 (complete year)	0.75	0.8	2.0	0.026

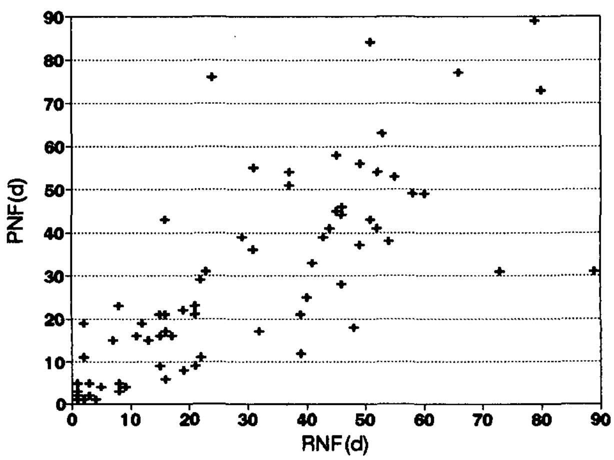

FIG. 3. Number of fires per day. Predicted (PNF) versus registered (RNF) values (July, August, and September) 1986.

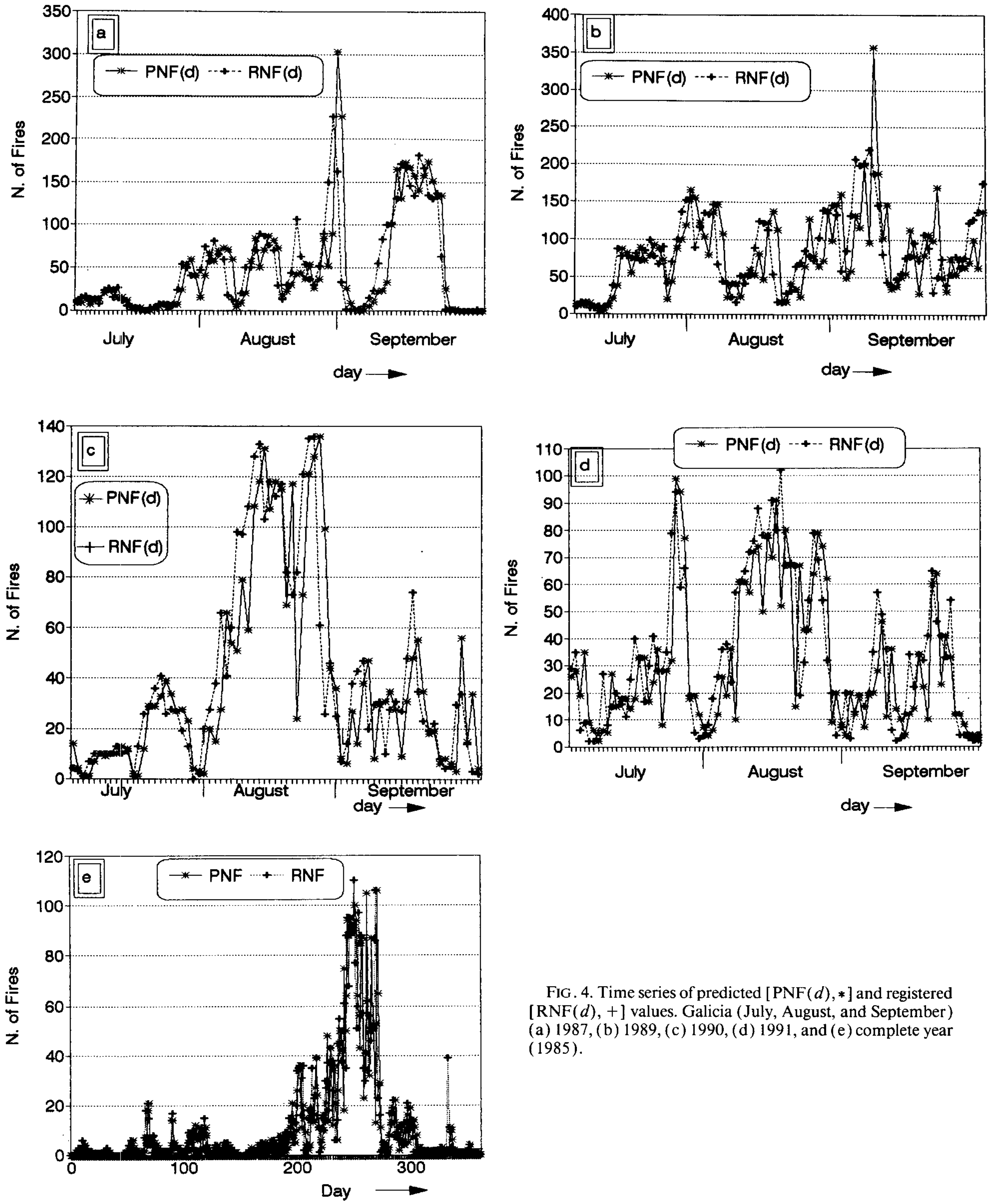

FIG. 4. Time series of predicted [PNF(d), $*$] and registered [RNF(d), $+$] values. Galicia (July, August, and September) (a) 1987, (b) 1989, (c) 1990, (d) 1991, and (e) complete year (1985).

regression analysis between the number of fires and the (e, D) index may be not representative. Furthermore, as has been explained, e presents two possible influences on the number of fire outbreaks. As a matter of fact, a regression analysis intended to obtain the predicted number of fires only on the

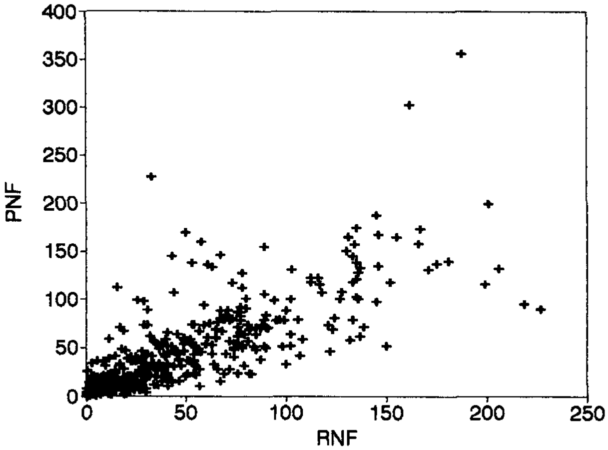

FIG. 5. Similar to Fig. 3 but for the total seasonal dataset (1986–91).

basis of (e, D) explained only a small part of the variance.

On the other hand, several factors such as previous drying sequences, precipitation deficit during previous months, and so forth play a very important role. Our index, defined on a day-to-day scale, ignores these factors. It would be surprising if two different days, with identical (e, D) values, one preceded by a dry period and the other preceded by a moist period, gave rise to the same number of fires. Our qualitative index must be interpreted in a relative sense. If a day is type I, the atmospheric conditions are much more favorable for the ignition of fires than if the day is type II. However, for each individual case, it is not possible to deduce a quantitative prediction for the number of fires per day.

From a forestry point of view it is accepted that fire occurrence (and, therefore, number of fires) is dependent upon two factors: risk and hazard. Risk is measured in terms of either lightning or potential fire starters (human). Hazard is determined by two factors: amount of fine fuel and fine fuel moisture.

A possible connection among our meteorological model and this forestry description is possible in terms of time scales. By definition, risk is a factor that may be associated with daily meteorological conditions (day-to-day scale). On the other hand, hazard is dependent upon a variety of factors including previous droughts or generalized precipitations over the area. In our model, these factors (more precisely, their effects over the area) are included in our concept of past weather.

3. Quantitative analysis

According to the preceding section, the number of forest fires registered during a particular day d depends upon two meteorological factors. The first factor is related to past meteorological conditions. Some conditions may prevail during long periods as droughts, hot spells, etc., and others may be more discontinuous in the time as generalized (or local) precipitations.

The second factor is exclusively related to daily meteorological factors, which may be described in terms of the (e, D) value.

Definitively, the number of fires per day $\mathrm{NF}(d)$ may be expressed as:

$$\mathrm{NF}(d) = \mathrm{PW}(d)W(d), \qquad (7)$$

in which $\mathrm{PW}(d)$ is the contribution due to the past weather conditions and $W(d)$ is the daily meteorological contribution. Accordingly, it is justified (7) that two isolated days, that is two days with very different past weather conditions $\mathrm{PW}(d)$ and the same (e, D) value (same type of day) present a very different number of fires. Moreover, it is possible to justify why two days with identical past weather conditions $\mathrm{PW}(d)$, present a notable difference in the number of fires. Evidently, it is due to the different past weather $\mathrm{PW}(d)$ and type of day, respectively.

Note that the meteorological perturbations that characterize past weather generally have a time scale longer than 2 days (for instance, drought, long dry periods associated with anticyclonic domains, etc.); thus, a realistic hypothesis for PW may be established for two consecutive days in the form:

$$\mathrm{PW}(d) = \mathrm{PW}(d-1). \qquad (8)$$

This assumption introduces an "inertial" sense (or persistence) that will play an important role in the operative prediction.

Since $\mathrm{NF}(d)$ is the number of fires per day, $\mathrm{PW}(d)$ can also be expressed in the same units; it follows that $W(d)$ is dimensionless.

a. Past weather (PW)

Determining $\mathrm{PW}(d)$ is a highly complex process, involving not only meteorological processes but also the peculiarities of each forest. It is well known that similar past meteorological conditions produce very different effects in two adjacent forests, and even in two different zones of the same forest. An additional complexity arises if the problem is a description of $\mathrm{PW}(d)$ in extensive areas (Galicia, for example), which present notable orographic irregularities, and a great variety of soil type and forestal species.

Diverse meteorological scales must be considered in this problem. In the mesoscale, many factors such as sea–land, land–sea (especially), valley–mountain, and mountain–valley breezes and the possible appearance of orographic dipoles, and downslope winds must be included. In the microscale, turbulent transfer processes must also be considered and, of course, we must take into account the synoptic situations that initially define the atmospheric circulation over forest.

In conclusion, in order to obtain a simple estimation of PW(d), a few restrictive assumptions must be established. These assumptions will be justified on the basis of statistical results.

According to (7) and (8), the predicted number of fires for the ($d-1$) day is

$$\mathrm{PNF}(d-1)=\mathrm{PW}(d-1)W(d-1). \quad (9)$$

If RNF($d-1$) is the registered number of fires on the ($d-1$) day, and supposing that the prediction was correct, then

$$\mathrm{PNF}(d-1)=\mathrm{RNF}(d-1), \quad (10)$$

it follows that

$$\mathrm{PW}(d)=\mathrm{PW}(d-1)=\frac{\mathrm{RNF}(d-1)}{W(d-1)}. \quad (11)$$

For the mean of this expression the past weather in d may be described in terms of the number of fires on ($d-1$) less its daily meteorological contribution. Consequently, using Eqs. (7), (8), and (11) we have

$$\mathrm{PNF}(d)=\frac{\mathrm{RNF}(d-1)W(d)}{W(d-1)}. \quad (12)$$

This equation indicates that the predicted number of fires for a day d is the number of fires registered during the preceding day ($d-1$) times a factor that depends only upon the ratio between the respective daily meteorological contributions.

In order to eliminate possible daily noise due to erroneous data in rawindsounding and/or the number of fires, a smoothing process must be introduced. In this sense, an iterative scheme in which PNF(d) presents an AR(2) (autoregresive mobile average of second order) form may be useful. Consequently, in (12) RNF$(d-1)[W(d-1)]^{-1}$ will be substituted by $0.5\{\mathrm{RNF}(d-2)[W(d-2)]^{-1}+\mathrm{RNF}(d-1)[W(d-1)]^{-1}\}$ with $d-2$ being 2 days before d. This is discussed in more detail in section 4. Definitively, the operative equation will be

$$\mathrm{PNF}(d)=\frac{1}{2}\left[\frac{\mathrm{RNF}(d-2)W(d)}{W(d-2)}+\frac{\mathrm{NFR}(d-1)W(d)}{W(d-1)}\right]. \quad (13)$$

b. Daily contribution W(d)

A daily meteorological contribution is introduced in this quantitative model in terms of the factor $W(d)$; This daily factor is based on the day-to-day analysis of the stability e at the 850–700-hPa layer and the saturation deficit D at the 850-hPa pressure level. In section 2, e and D have been defined from a theoretical point of view. Further, several statistical considerations were discussed. In an operative sense, for each day at 0000 UTC the day type is established on the basis of a categorization (I, II, III, or IV). When considering the daily effect, the following question must be answered: if a day d was type II and RNF(d) was the number of fires registered in this day, what would have been the number of fires if this day had been type I? In other words, a weight for each type day, according to the categorization, must be fixed.

From different datasets, monthly, seasonal, and total, (García Diez et al. 1993) during the period 1981–85 we found that

$$\mathrm{DFR(I)}>\mathrm{DFR(III)}>\mathrm{DFR(IV)}>\mathrm{DFR(II)}. \quad (14)$$

If a normalized daily fire risk (NDFR) for each type day (i) is defined as

$$\mathrm{NDFR}(i)=\frac{\mathrm{DFR}(i)}{\sum_j \mathrm{DFR}(j)},\ (i,j=\mathrm{I,II,III,IV}), \quad (15)$$

the average numerical values are

$$\mathrm{NDFR(I)}=0.4\quad \mathrm{NDFR(II)}=0.1$$
$$\mathrm{NDFR(III)}=0.3\quad \mathrm{NDFR(IV)}=0.2. \quad (16)$$

With these results the above-mentioned question is easily answered. In effect, if the day would had been type I, the number of registered fires, RNF(d), would verify the relationship $\mathrm{NDFR(I)}[\mathrm{NDFR(II)}]^{-1}=4\mathrm{RNF}(d)$.

Clearly, the daily meteorological factor $W(d)$ may be associated with NDFR as follows,

$$W(d)=a\mathrm{NDFR}(d), \quad (17)$$

where a is a constant of proportionality. Knowledge of the particular value of a is not relevant. Indeed, when (17) is introduced into (13), a disappears.

c. Operative method

Based on the above discussion, the operative method can be described in the following way. We consider a particular day d at 0000 UTC, at which it is given:

(i) rawinsounding data (at 0000 UTC);
(ii) the type day for two preceding days ($d-2$ and $d-1$);
(iii) the number of registered fires for two preceding days [RNF($d-2$) and RNF($d-1$)].

From (i), (e, D) is immediately evaluated and, therefore, the type day for d is known according to the above-mentioned categorization.

At this point, the following possibilities can be discussed:

1) Possibility 1 is that $d-2$, $d-1$, and d present the same type day. This implies $W(d)=W(d-1)=W(d-2)$ and from (13) and (17) it is obtained that

$$\mathrm{PNF}(d) = \frac{1}{2}\frac{\mathrm{RNF}(d-2) + \mathrm{RNF}(d-1)W(d)}{W(d-1)}$$
$$= \frac{1}{2}\frac{\mathrm{RNF}(d-2) + \mathrm{RNF}(d-1)\mathrm{NDFR}(d)}{\mathrm{NDFR}(d-1)}$$
$$= \frac{\mathrm{RNF}(d-2) + \mathrm{RNF}(d-1)}{2}. \quad (18)$$

2) Possibility 2 is that $d-2$ and $d-1$ present the same type day and d a different type day. In this case, since $W(d-1) = W(d-2)$,

$$\mathrm{PNF}(d) = \frac{1}{2}\frac{\mathrm{RNF}(d-2) + \mathrm{RNF}(d-1)W(d)}{W(d-1)}$$
$$= \frac{1}{2}\frac{\mathrm{RNF}(d-2) + \mathrm{RNF}(d-1)\mathrm{NDFR}(d)}{\mathrm{NDFR}(d-1)}, \quad (19)$$

where the ratio $\mathrm{NDFR}(d)[\mathrm{NDFR}(d-1)]^{-1}$ is immediately obtained from (16).

3) Possibility 3 is that $d-2$ and $d-1$ are each a different type day and one of these type days is the same as d. Let $W(d-1) = W(d)$, then

$$\mathrm{PNF}(d)$$
$$= \frac{1}{2}\left[\frac{\mathrm{RNF}(d-2)W(d)}{W(d-2)} + \frac{\mathrm{RNF}(d-1)W(d)}{W(d-1)}\right]$$
$$= \frac{1}{2}\left[\frac{\mathrm{RNF}(d-2)W(d)}{W(d-2)} + \mathrm{RNF}(d-1)\right]. \quad (20)$$

4) Possibility 4 is that $d-2$, $d-1$, and d are each a different type day. In this case,

$$\mathrm{PNF}(d)$$
$$= \frac{1}{2}\left[\frac{\mathrm{RNF}(d-2)W(d)}{W(d-2)} + \frac{\mathrm{RNF}(d-1)W(d)}{W(d-1)}\right]$$
$$= \frac{1}{2}\left[\frac{\mathrm{RFN}(d-2)\mathrm{NDFR}(d)}{\mathrm{NDFR}(d-2)} + \frac{\mathrm{RFN}(d-1)\mathrm{NDFR}(d)}{\mathrm{NDFR}(d-1)}\right]. \quad (21)$$

4. Validation of the model

In order to establish the validity of the theoretical model described in previous sections, we present here several statistical computations that must justify the hypothesis assumed.

In this study Galicia, Spain, is considered a testing area for several objective reasons, mainly because in this zone the high number of fire outbreaks per day is a crucial problem. In addition, a rawinsounding station is located in Galicia (specifically in La Coruña, TEMP 08001). This is a requirement for the model.

The question that must be answered is whether or not the rawinsounding of La Coruña is representative of the four provinces in which Galicia is divided. The precise knowledge of the zonal validity of a rawinsounding is a highly complex problem. For our purposes an indirect, but realistic, method would be an analysis of regression between time series of the numbers of fires daily in each province (Table 2).

As can be seen, the average coefficients for each month have a significant value. Thus, it is possible to consider Galicia as a closed zone in the sense that fire activity may be described in terms of the La Coruña rawinsounding.

Also, in order to prove the validity of the operative method it is necessary to dispose of a dataset that is independent with respect to the dataset used for obtaining the daily contributions $W(d)$. Since the dataset that was considered for establishing the categorization and $W(d)$ in terms of NDFR was from 1981 to 1985, we will consider 1986–91 as the dataset (1988 is not included because the necessary data were not available).

The validity of our predictive equation (13) may be noted by comparison between forecasting the number of fires and the corresponding registered values. Initially, a seasonal scale that includes July–August–September for each year is considered. If a regression analysis between PNF(d) and RNF(d) is applied in the form PNF(d) = (slope)RNF(d) + intercept, the results obtained are highly significant, as noted in Table 3. Concretely, r^2 values are centered in the 0.60–0.70 interval, implying a strong temporal stability of the predictive model. Notice also the high homogeneity that presents the slope, intercept, and the standard error in the correlation.

In a more precise form, Fig. 3 shows PNF(d) versus RNF(d) for 1986. The general tendency is acceptable, specifically if it is noted that there exists a similar quality in low, moderate, and high activity. Only in a few cases does a notable error appear in the prediction.

Figures 4a–d simultaneously show the temporal series of PNF(d) and RNF(d) corresponding to 1987, 1989, 1990, and 1991. For each case, similar conclusions to those deduced for 1986 may be emphasized.

If a total seasonal dataset is considered, more than 430 predictions are included; the results are shown in Fig. 5.

We also analyzed the possible quality of the model through a complete year (363 predictions; the model is run on the third day). In this case months with very low activity are also included. In Table 3 we included the results obtained for 1985 and it is noticeable that $r^2 = 0.75$. The respective temporal series are also shown in Fig. 4e.

In conclusion, this forecast method could be applied in other geographic areas. The only preliminary requisite is to determine the particular values of NDFR for each area. The precise knowledge of NDFR requires, as discussed in section 3, a minimum dataset of 5 years (July, August, September). Thus, the model may be operative in real time from data derived from appropriate rawinsounding and RNF($d-2$), RNF($d-1$) in the area.

This method may be used in connection with global programs such as NFDRS (National Fire Danger Rating System) (Deeming et al. 1977) and BEHAVE (Fire Behavior Prediction System) (Andrews and Bradshaw 1991), both well known in the literature.

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