Meteorology and Forest Fires: Conditions for Ignition and Conditions for Development

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ABSTRACT

Following the theoretical model proposed in previous papers in which four types of days and their associated fire risk (daily fire risk, DFR) were defined for each size of fire, the authors conclude that the meteorological conditions that favor the generation of fires must be similar to those that are favorable to their development. In a study of burned areas, comparative results with previous works are obtained, and the parameters DFR and NDFR (normalized DFR) are proven to be in agreement with their previously assigned physical meaning. The development rather than the ignition of forest fires is better described using the DFR and NDFR parameters.

1. Introduction

Forest fires, especially in southern Europe, play a significant role from an environmental point of view. In recent decades this problem has been analyzed in a synoptic sense by Brotak and Refsnyder (1977) and Brotak (1980) deducing that particular synoptic situations are associated with the fire activity. In an operative sense, there are risk indices to describe the possibility of ignition (Palmieri and Cozzi 1983). Also, there are bibliography models such as Lower Atmospheric Severity Index (Haines 1988) or BEHAVE (Andrews and Bradshaw 1991) that describe the fire development. As a first scheme, two problems or processes must be considered: ignition and development. For a given zone, the problem of ignition may be analyzed in terms of forecasting of the daily number of forest fires (E. García Diez et al. 1994; A. García Diez et al. 1995, 1996). This prediction is more useful than other qualitative indices. On the other hand, the fire development is meteorologically described on the basis of wind behavior. It is accepted by the scientific community that fire ignition is associated with temperature, humidity, and/or other parameters, and fire development is associated with wind. To obtain a risk scale, in an earlier paper (García Diez et al. 1993) a classification in four types of day was established on the basis of atmospheric stability and humidity in lowest atmospheric layer. Particularly, the stability in the lower layers is a good parameter for detecting possible upward motions. If other parameters are fixed, the heat released by a fire implies an upward movement or vertical divergence of the air that itself organizes, according to the equation of continuity, a horizontal convergence of air below. Evidently, this convergence is a wind that could play a more important role than the synoptic wind. For this reason, the fire development would be explained in terms of the stability in the local atmospheric column. This hypothesis will be analyzed here.

In this study, fire and meteorological data are analyzed from the northwest region of Spain, that includes the provinces of Asturias, Cantabria, La Coruña, Lugo, Orense, Pontevedra, León, and Zamora. In these areas, the problem of forest fires requires a statistical study due to the very high number of forest fires registered per day. For each year only the months of July, August, and September are considered because they are the ones with the most fire activity.

A critical point in this study is to investigate, on the basis of a model that explains the ignition for all fires (the burned area is not included), how the type of day is meteorologically important to the development of large fires. As will be seen, large fires occur principally during days with high risk. Consequently, the meteo-

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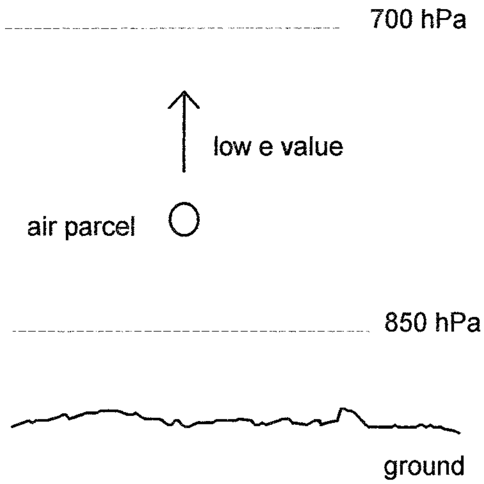

FIG. 1. Ascendent motion is associated with low e values.

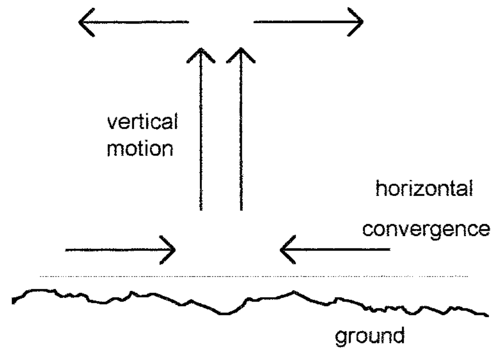

FIG. 2. Horizontal convergence and vertical divergence at lowest layer. Fire scheme.

rological conditions associated with development (essentially the synoptic wind) are coupled with the meteorological conditions for ignition.

2. Theoretical model

a. Stability in the 700–850-hPa layer

The atmospheric energetic state at one point can be determined considering an air bubble with unit of mass. Its total energy is given by

$$E_T = C_P T + gz + \frac{1}{2}v^2 + Lq + L_S q, \qquad (1)$$

where $C_P T$ is the enthalpy, gz the potential energy, $(1/2)v^2$ is the kinetic energy, Lq the energy released in condensation, $L_S q$ the energy released in solidification, and q the specific humidity of water vapor.

The "dry static energy" or Montgomery potential (Montgomery 1937) is defined as

$$S = C_P T + gz. \qquad (2)$$

The vertical profile of dry static energy versus p can be taken as an atmospheric stability index for a dry layer (Arakawa and Schubert 1974) and is given by

$$e' = -\frac{\partial S}{\partial P}. \qquad (3)$$

Thus, the stability criterion is

$$\frac{\partial S}{\partial P} > 0 \Rightarrow e' < 0, \qquad \text{unstable}$$

$$\frac{\partial S}{\partial P} = 0 \Rightarrow e' = 0, \qquad \text{neutral}$$

$$\frac{\partial S}{\partial P} < 0 \Rightarrow e' > 0, \qquad \text{stable.} \qquad (4)$$

To avoid orographic problems (very variable altitude, unhomogeneity of the soil, etc.), the 700–850-hPa layer may be considered as the lowest one. Consequently e', defined as follows, may be used as a stability index over soil:

$$e' = -\frac{S_{700} - S_{850}}{700 - 850} = -\frac{S_{700} - S_{850}}{-150} = \frac{e}{150}, \qquad (5)$$

in which $e = S_{700} - S_{850}$.

If the atmospheric column is very stable, the value of e is very high, vertical (convective) motion is quite difficult (Fig. 1). On another hand, the continuity equation is

$$\frac{1}{\rho}\frac{d\rho}{dt} + \nabla\cdot\mathbf{v} = 0. \qquad (6)$$

If the atmosphere is incompressible then $\nabla\cdot\mathbf{v} = 0$, so the flux is not divergent. Because the problem is defined in three dimensions, horizontal convergence forces vertical divergence and reciprocally. If this process happens in the lowest atmospheric level, then the vertical divergence is an upward movement (Fig. 2). Generally speaking, the atmosphere presents stability in all layers, particularly in the one considered (850–700 hPa).

The energy required of an air parcel to move from a level A to a level B (Fig. 3), by solar or fire heating, is given by

$$\Delta E_{AB} = \int_A^B \frac{\partial S}{\partial P}\, dP. \qquad (7)$$

If, in a local column of the atmosphere the Montgomery potential S is a linear function of p (Arakawa and Schubert 1974; Rivas Soriano and García Diez 1993), then $\partial S/\partial P$ is constant and

$$\Delta E_{AB} = \int_A^B \frac{\partial S}{\partial P}\, dP = \int_A^B \frac{dS}{dP}\, dP. \qquad (8)$$

Solving the integral, one can obtain

$$\Delta E_{AB} = S_B - S_A. \qquad (9)$$

If the stability between two levels is defined as $e =$

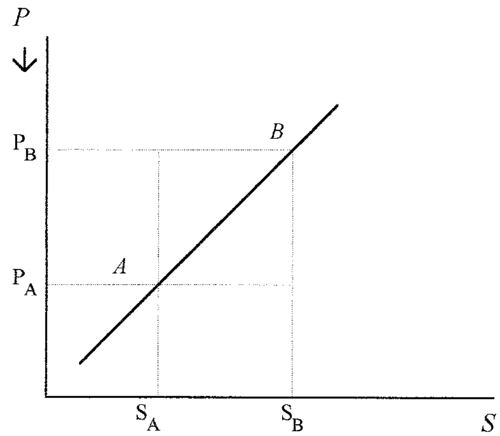

FIG. 3. Graphic of P versus S according to the stability criterion [Eq. (5)].

$S_B - S_A$, then using (5) and (9), the stability is given by

$$e = S_B - S_A = \Delta E_{AB}. \tag{10}$$

This equation, together with (8), shows that the energy needed by the parcel is exactly the stability of the atmospheric column

$$\Delta E_{AB} = S_B - S_A = e = 150e'. \tag{11}$$

If one is able to demonstrate that e and e' are the same, the only difference between them is a constant (ΔP), and then the stability criterion given in (4) for e' is the same for e. So, when the defined value of the stability (e) is low, the energy required to raise the particles obviously decreases.

Thus, when the air is heated by fire at the initial instant, this energy is transferred to the overlaying atmosphere and transformed into vertical kinetic energy. The maximum height of vertical motion depends inversely upon e. According to the continuity Eq. (6), the elevation of the air mass implies the convergence of air over the soil. This convergence, for a given fire, depends only on the value of e, and the higher the velocity of the bubble is, the stronger the convergence in low levels will be. This implies, in an operative sense, that during days with low e values the flames will be higher and the wind stronger due to surface convergence.

In conclusion, the ignition forces an upward motion, which will be stronger when the lowest atmospheric layer (i.e., 850–700 hPa) is unstable or presents low stability (low e values).

b. *Humidity at low levels*

Another parameter in the atmosphere is the quantity of water vapor. As it is well known, humidity may be expressed in very different forms. Here, for reasons of homogeneity in units, it is considered as the saturation deficit D, given by

$$D = (h^* - h)_{850} = L(q^* - q)_{850}, \tag{12}$$

in which

$$h = C_P T + gz + Lq$$

and

$$h^* = C_P T + gz + Lq^* \tag{13}$$

are the moist (h) and the saturated (h^*) static energies; q and q^* are the specific humidity and saturated specific humidities, respectively. These energies, defined in this way, verify that $h \leq h^*$. Consequently, D gives information about atmospheric humidity: high D implies less humidity and low D implies more humidity.

Clearly, a day with a high D value will be more adventageous to fire than a day with a low D value. Experimentally, as can be easily verified, hot months have more insolation and evaporation and they are less stable than cold months (a very hot soil destabilizes the atmospheric column above it). Therefore, these months present more fire activity, and the antifire campaigns start in summertime. Sometimes, the conditions described here are not present altogether in summer. There are some locations in the north of Spain such as Guipúzcoa in which these conditions occur in months like February and March because of its local Monzonic circulation. In winter the sea surface temperature (SST) is higher than land temperature and, consequently, this thermal gradient implies a low-level land–sea circulation that introduces dry air over area. This is a good example for demonstrating that the temperature alone does not determine fire risk.

Notice that these two parameters, e and D, are defined homogeneously in energy per mass (kJ kg^{-1}). This is an important property, because if other parameters (wind, solar radiation, etc.) were considered, these new parameters could be easily introduced: in terms of energy per unit of mass.

c. *Categorization of days and DFR*

On the basis of statistical and physical considerations, the average values of e and D for summer months (July, August, and September) are

$$e \cong 6.7 \text{ kJ kg}^{-1} \text{ and } D \cong 11.8 \text{ kJ kg}^{-1}.$$

Statistically, when several summer periods are considered, the average values obtained for (e, D) are included in the intervals 6.1–7.1 and 11.4–13.8, respectively. Because the error in radiosonde record is higher, more precision in this point would not be useful. On other hand, the values $e = 6$ kJ kg^{-1} and $D = 12$ kJ kg^{-1} are very coherent physically with the results for the area of the U.S. standard atmosphere (NOAA-NASA-USAF 1976).

In this way, four types of days are determined, as seen in Table 1.

An operative index, daily fire risk (DFR), is defined as

TABLE 1. Types of days.

e (kJ kg^{-1})	D (kJ kg^{-1})	Denomination	Type of day
≤ 6	≥ 12	Unstable dry	I
≤ 6	<12	Unstable moist	II
>6	≥ 12	Stable dry	III
>6	<12	Stable moist	IV

$$\mathrm{DFR}_i = \left(\frac{\text{number of fires}}{\text{number of days}}\right)_i \quad (i = \mathrm{I, II, III, IV}). \tag{14}$$

It is found that

$$\mathrm{DFR_I} > \mathrm{DFR_{III}} > \mathrm{DFR_{IV}} > \mathrm{DFR_{II}}. \tag{15}$$

Therefore, at the beginning of the day, each day can be easily classified: if it is a type I day the risk is ''very high''; a type III day, the risk is ''high''; a type IV day, ''low''; a type II day, ''very low.''

3. Categorization of days: Ignition and development

Data about the surface burned for each fire are provided by ICONA (Instituto Nacional para la Conservación de la Naturaleza; 1994). First, all the fires have been considered. A normalized daily fire risk (NDFR) for each type of day is defined as

$$\mathrm{NDFR}_i = \frac{\mathrm{DFR}_i}{\sum_j \mathrm{DFR}_j} \quad (i, j = \mathrm{I, II, III, IV}), \tag{16}$$

and the following average numerical values for the period 1988–93 have been obtained:

$$\begin{aligned} \mathrm{NDFR_I} &= 0.4 \qquad \mathrm{NDFR_{II}} = 0.1 \\ \mathrm{NDFR_{III}} &= 0.3 \qquad \mathrm{NDFR_{IV}} = 0.2. \end{aligned} \tag{17}$$

These NDFR values must be interpreted in a relative sense: a type I day tends to present four times more fire activity than a type II, and so on. This is a very important point in statistical partitioning processes. The four types of day that have been defined present the same ''risk interval.'' Consequently, the partition established in the (e, D) plain seems to be a good one.

Forest fire size is now taken into consideration. Several series C_k (92 days, from 1 July to 30 September for k years) are considered and assigned to each element of another series F_k (number of registered fires per day during year k). Each series C_k is divided in four classes (types of days) and for each class a property (DFR_k) is defined. This property becomes an ordered relation (15), and it is well defined if all days and all registered fires each day are considered for any year. Thus, the NDFR is defined as a universal property of each type of day.

The next question arises as follows. If an unusual and restrictive selective criterion is introduced (burned surface) over the number of registered fires, will the order of the relationship for the DFR be maintained? The following different possibilities must be considered.

- If the unusual criterion applied on C_k and F_k selects all elements (as an example: let the fires with a burnt surface be greater than or equal to 0), the relational order is obviously conserved.
- If the unusual criterion selects a few elements of each type (5%–10%)—that is, when only large fires are considered—the order relationship for DFR must break down.

Therefore, when some forest fires are chosen with a very restrictive criterion, the most likely situation is that the order between the DFRs may be different than (15). If this relation is not verified, it must be deduced that the daily fire risk describes well all the fires (ignition) but not the large ones. Consequently, the meteorological conditions considered in the definition of DFR describe the ignition well but do not describe correctly the development of fires.

If (15) holds, it may be deduced that the days with a higher number of fires are also those that register the largest ones. This means that DFR is a good way to analyze simultaneously ignitions and development of fires; that is, the meteorological conditions of ignition and development are not very different.

However, the question arises about what happens if the relation of DFR for large fires is stronger than the one for all fires? As will be seen later, this is the principal result of this paper. A strong connection between ignition and development conditions is found and, more precisely, the classification established for the meteorological conditions in the model are better associated with fire development than with ignition.

The provinces considered in this work have two main characteristics in terms of fire activity: (i) They typically have a high number of forest fires per day and (ii) the burned surfaces are small ($<10^4$ m^2). For this last reason, a realistic classification for large fire may be those fires with burned surface areas of at least 10 ha. Other studies were conducted on the basis of burned surfaces of at least 15 ha and 20 ha.

The results obtained are shown in Table 2 in which the DFRs appear for the respective subseries of big fires (a, c, and e) versus the DFRs for the respective complementary subseries—that is, for fires less than these in size (b, d, and f).

The DFRs for all types of days verify the following relationship,

$$\begin{aligned} \mathrm{DFR_I} &\gg \overline{\mathrm{DFR}} \qquad \mathrm{DFR_{III}} \cong \overline{\mathrm{DFR}} \\ \mathrm{DFR_{IV}} &< \overline{\mathrm{DFR}} \qquad \mathrm{DFR_{II}} \ll \overline{\mathrm{DFR}}, \end{aligned} \tag{18}$$

where the $\overline{\mathrm{DFR}}$ are obtained by averaging the total number of fires by the total number of days (92), thus giving the mean fire risk each year by size of fire. This means that the fire risk of a type I day is bigger than the mean risk, the risk of a type III is very similar to the mean (this agrees with the result that type III days are the

TABLE 2. DFR for the different sizes of fires.

Year	I	II	III	IV	Mean
(a) Forest fires larger than 10 ha.					
1988	5.04	0.00	1.09	0.69	1.92
1989	14.14	3.43	13.72	5.30	11.27
1990	5.16	0.50	3.58	0.83	3.54
1991	1.10	0.15	0.54	0.61	0.68
1992	0.27	0.00	0.16	0.02	0.11
1993	1.20	0.00	0.12	0.02	0.30
1994	1.08	0.66	0.61	0.29	0.51
Mean	4.00	0.68	2.83	1.11	
(b) Forest fires smaller than 10 ha.					
1988	81.09	0.00	24.59	16.17	35.51
1989	76.78	30.71	75.17	52.30	67.44
1990	55.22	15.00	52.03	25.11	46.43
1991	54.53	13.31	45.38	25.65	38.90
1992	41.67	1.00	26.53	13.23	22.36
1993	97.45	20.25	54.76	18.02	45.37
1994	101.77	9.00	86.50	49.52	66.84
Mean	72.64	12.75	52.13	28.57	
(c) Forest fires larger than 15 ha.					
1988	3.09	0.00	0.91	0.51	1.30
1989	10.81	2.14	10.21	3.50	8.37
1990	4.05	0.25	2.82	0.78	2.80
1991	0.73	0.08	0.50	0.48	0.62
1992	0.20	0.00	0.09	0.00	0.07
1993	0.90	0.00	0.04	0.02	0.22
1994	0.77	0.66	0.36	0.27	0.38
Mean	2.94	0.45	2.13	0.79	
(d) Forest fires smaller than 15 ha.					
1988	83.04	0.00	24.76	16.63	36.24
1989	80.11	32.00	78.69	54.10	70.35
1990	51.30	12.00	47.12	21.06	42.17
1991	54.83	13.38	45.42	25.65	39.02
1992	41.73	1.00	26.59	13.25	22.40
1993	97.75	20.25	54.84	18.02	45.46
1994	101.31	9.00	86.71	49.58	66.87
Mean	72.87	12.52	52.02	28.32	
(e) Forest fires larger than 20 ha.					
1988	2.13	0.00	0.68	0.31	0.90
1989	8.61	1.57	8.07	2.85	6.65
1990	3.38	0.25	2.18	0.56	2.26
1991	0.57	0.08	0.46	0.35	0.41
1992	0.20	0.00	0.09	0.00	0.07
1993	0.60	0.00	0.04	0.02	0.15
1994	0.62	0.33	0.36	0.21	0.32
Mean	2.30	0.32	1.70	0.61	
(f) Forest fires smaller than 20 ha.					
1988	84.00	0.00	25.00	16.26	36.42
1989	82.31	32.57	80.83	54.75	72.06
1990	56.89	15.50	53.30	25.33	47.63
1991	55.00	13.38	45.46	25.78	39.12
1992	41.73	1.00	26.59	13.25	22.40
1993	98.05	20.25	54.84	18.02	45.52
1994	102.23	9.33	86.71	49.62	67.03
Mean	74.32	13.15	53.24	29.00	

mean type of day from a meteorological sense), the risk of type IV day is less than the mean and the risk of type II is much less than the mean.

Using the definition (16), the NDFRs are calculated, obtaining the results in Table 2 for all the years and each size of fire.

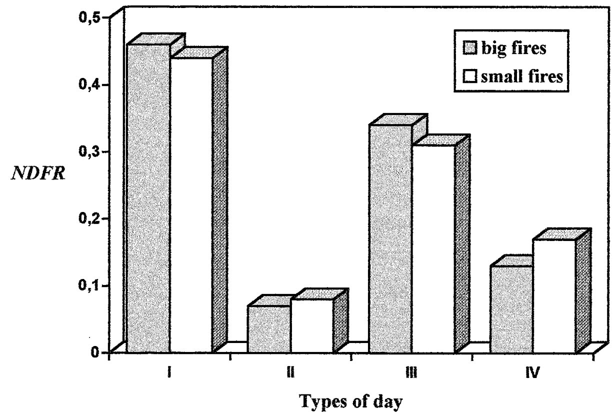

FIG. 4. Normalized daily fire risk (NDFR) for different fire sizes.

For any filter, comparing the NDFRs obtained for these subseries (large fires) with the ones for the complete series (all fires), it can be seen that

$$\mathrm{NDFR}_{\mathrm{I,III}\ (\mathrm{subseries})} > \mathrm{NDFR}_{\mathrm{I,III}\ (\mathrm{series})}$$

$$\mathrm{NDFR}_{\mathrm{II,IV}\ (\mathrm{subseries})} < \mathrm{NDFR}_{\mathrm{II,IV}\ (\mathrm{series})}.$$

Graphically, this result is shown in Fig. 4. Thus, the meteorological conditions corresponding to I and III days, which are the most favorable for ignition, also are more favorable for development. And, in contrast, the conditions corresponding to days II and IV, that are the less favorable to the ignition, are even less favorable for large fire development.

The most important difference between classes I and III, and between II and IV, respectively, is humidity. When a fire has been ignited, it generates its own circulation and the stability of the initial atmospheric column becomes less important: the humidity becomes the most important parameter for development.

Consequently, the development process is better described than ignition by the DFR. Physically, it means that the meteorological conditions that favor the ignition of forest fires are not very different from the conditions that favor the development.

4. Conclusions

In this paper the dualism between *ignition* and *development* of forest fires has been analyzed. On the basis of statistical considerations, a parallel between meteorological conditions for both processes is shown. More precisely, DFR defined by considering the ignition risk appears to be a very good indicator of the development risk. Consequently, the colloquial opinion in both the operational and scientific communities that ''*days with a high number of fires are also those that contribute to more burned area,*'' is shown to be true for fires and meteorology investigated in northwestern Spain.

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