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Fire Spread Experiment Across Mediterranean Shrub: Influence of Wind on Flame Front Properties

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Abstract

A fire spread experiment was conducted in the field under wind-blown conditions. The study area was located in south Corsica (France). The fuel consists in tall and dense Mediterranean shrub vegetation. The plot area was about 30 m wide and 80 m long. The fire spread experiment was made using a point ignition. This experiment was conducted not only in order to increase the knowledge and understanding of the fire behaviour in the field but to provide data for the validation of physics based models of fire spread too. In particular, the effects of wind on the geometric and thermal properties of the flame front in the field are investigated. The flame temperature along the vertical direction and the radiation emitted ahead of the flame front, were measured. The methodology employed in this experiment and some quantitative measurements of wind velocity and direction, flame geometric properties, are also presented and discussed.

Keywords: fire experiment; field scale; shrub; wind; temperature; radiant heat flux

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1. Introduction

In forest fire research, the experimental studies of the fire spread across vegetal fuels are of great interest for understanding and modelling the fire behaviour. The fire spread experiments across beds of fuel at laboratory scale have generated an abundant and miscellaneous literature from the last fifty years [1-11]. In these laboratory experiments (fuel bed area lower than 10 m^2), each run can be conducted under controlled conditions (homogeneous fuels, controlled wind...) and their instrumentation is quite easy to implement. These works were mainly devoted to study the effect of fuel moisture content, slope and wind velocity on the fire spread and flame properties. The university of Corsica team also conducted a set of laboratory experiments across beds of fuel [12-14] in order to collect data on fire properties which could be useful for the validation of physics based models of fire spread. The experimental method used was based on temperature measurements within the flame, heat fluxes measurements ahead of the fire front and infrared imaging.

At present time, there is a need of valuable data on fire spread at a scale larger than the laboratory one. Some documentation on the spread of forest fires can be found in the literature. These reports made from fire observations [15] or monitoring with satellite imagery within the infrared band [16] showed at best the fire shape history and associated meteorological and fuel conditions. Nevertheless, all of these data are not easy to use for modelling purpose and few experimental studies at field scale were conducted in this way up to now. The major part of these studies only provides observations or measurements of the macroscopic characteristics of the flame front (rate of spread, flame length, flame tilt angle, residence time...) because instrumentation in the field is more difficult. The measurements done during these experiments are summarised in Table 1. Cheney and

Gould [17-18] studied fire growth in open grassland and related the rate of spread to the head of fire width. Theses pioneer works, which show a significant influence of the fire front shape and size on its spread, confirm that field experiments are the best alternative for the understanding of real fire behaviour. Carrega [19] also believes that measurements in the field are of great interest and developed a rate of spread and weather measurement protocol which can be used in wild fires or prescribed burning. Viegas [20] conducted a set of experiments across shrub vegetation to study the effects of vegetation, type of ignition, slope and wind on fire behaviour. De Luis [21] concentrated its efforts on the characterization of the vegetative structure and analyse fire behaviour across shrublands using this indicator. On the other hand, some recent studies began to include measurements of thermodynamic quantities. In particular, Alexander [22] and Cohen [23] conducted crown fire experiments and instrumented wooden walls with heat flux sensors to provide information on the forest fire threat to homes.

The data on the spread of real-size fires are thus quite rare and experiments in the field have to be conducted to improve the knowledge of the mechanisms of forest fire spread. For instance, contradictory assumptions can be found in the literature concerning the nature of the dominant heat transfer mechanism under wind blown conditions: on one hand, Anderson and Rothermel [24] attributed the increase in rate of spread to increased radiation impinging on the fuel due to the tilted flames; on the other hand Fendell [25] indicated that convection is the principal heat transfer mechanism based on analysis of experimental data; while Pagni and Peterson [26] concluded that radiative transfers from overhead flames dominate the heat transfer processes at low wind speed but that convection becomes dominant as the wind velocity increases. Only quantitative measurements will allow to answer to the question of knowing which process contributes for the major part of the heat required to fire spread. Data collection in the field appears to be the better way to improve and validate the fire spread models. Weber [27] classified them into three types (statistical, empirical and physical models). The field experiments or wildfire observations, which provide some macroscopic descriptors, can be sufficient for the validation of the first two kinds of model since no thermodynamic quantity is needed. On the other hand, the physical models [28-30] based on a set of conservation equations, need more precise data on thermodynamic quantities (like temperatures or heat fluxes involved in the fire spread) to be improved or validated. Although much progress has been made, more remains to be accomplished for the development of physical model that account for the behaviour of a forest fire. Moreover, the field scale predictions of the fire spread models, which have been validated against laboratory experiments data, must be considered with caution. Indeed, the fire front intensity, the magnitude of heat transfers and the turbulence effects (which play a significant role on fire spread and in particular on the combustion processes) involved at laboratory scale are not the same in the field. The development of sub-models (thermal degradation of the vegetation...) from laboratory scale data, in conditions which are not representative of the one encountered in the field (small samples, low rate of temperature increase...), should also be carefully considered.

These considerations have provided the main motivation for the present work to generate valuable data on the fire at field scale. A fire spread experiment was conducted across Mediterranean shrub and data were collected following the method detailed in [31]. In the present work, the data collected with different kinds of sensors during the fire spread, are presented and discussed. In particular, the effects of wind on the geometric and thermal properties of the flame front are investigated. The study of the wind effects on the fire is of great interest since buoyant flames in the open space, are nearly always exposed to a cross-wind. The wind influence on the overall behaviour of the fire is well known. The observations showed that the wind brings the flames closer to the unburned fuel and significantly influences the heat transfer processes. As a result, the fire rate of spread increases dramatically with increasing wind. The effects of wind turbulence on the flame front are not frequently described as mentioned by Pitts [32]. Nevertheless, the fully developed turbulence is an essential character of wind flowing on a natural ground and significantly affects the fire spread as well as the flame shape, temperature and radiation emission. In order to assess the characteristics of the wind and its effects on fire, anemometers were placed around the plot. The temperature measurements inside and above the vegetation were done with thermocouples. The radiant heat fluxes were also measured ahead of the flame front. Digital video cameras recorded images of the fire from the side and front view to determine the flame geometry. In order to help to obtain more accurate observations, an infrared camera was also used.

2. Experimental procedure

2.1 Study area

The fire spread experiment was conducted in the field on July 2004. The study area was located in south Corsica (France) near Porto-Vecchio (41°41'10"N, 9°20'47"E) on a varying slope facing northwest. The first part of the terrain was 23° up-slope and the other one was on a relatively flat terrain (4° up-slope). The plot was located at 2 km from the sea and its altitude was about 100 m above the sea level. The site description was fully provided in [31]. The plot area was about 30 m wide and 80 m long. For security reason, 20 m wide firebreak were made and firemen posted around the plot during the experiment (Fig. 1).

The fuel consisted in tall (about 2.5m high) and dense Mediterranean shrub vegetation in which the dominant species were *Olea europea, Quercus ilex, arbustus unedo, Cistus monspeliensis, and Cytisus triflorus.* The estimated total biomass was about 10 kg/m^2. A cartography of the vegetation cover was made using transept method. The composition and properties of the vegetal cover are detailed in [31]. Exceptional rainfall (between 75 and 100 mm) during may 2004 resulted in high moisture content of the vegetation leaves during the experiment. The fuel moisture content was obtained from 50 samples for the five most abundant species thanks to a thermobalance. The average value for these species ranged from 67 to 108% of dry weight.

The different sensors, connected to a data logger, are described subsequently. The data logger was placed at the centre of the measuring section, at 12 m from the edge of the plot vegetation (Fig. 1), in order to minimize the sensors cables length. A single data logger was used to insure data synchronisation. It was located inside a fireproof housing cooled by forced air circulation, to prevent it from the flames and thermal radiation emitted by fire front.

2.2 Thermocouples

The flame temperature along the vertical direction was measured with three sets of thermocouples located inside the vegetation and spaced 6 m apart (Fig. 1). The measuring section was located approximately 1 m before the end of the vegetation. This positioning was chosen to provide a relevant characterisation of the flame front when it reaches the vegetation/firebreak interface. The insulated supporting rods (6.1 m high) were prepared to hold ten thermocouples spaced 0.6 m apart; the first thermocouple being located 0.6 m from the soil (Fig. 2). The thermocouples were inserted through a ceramic insulator and a stainless steel protection tube. The thermocouple junctions horizontally protrude about 4 cm from this tube and were vertically aligned. Measurements were done both in the flame and plume regions using K-type ungrounded thermocouples with 50 μm wire diameter. The three first thermocouples were located inside the shrub and the seven others were above the vegetation. The sampling rate was 100 measurements per second per thermocouple.

2.3 Heat flux sensors

The experiment was also carried out to measure the contributions of convection and radiation ahead of the flame front. To this end, three rows of three sets of heat flux sensors, spaced 5 m apart, were located ahead of the vegetation (Fig. 1). The sets of sensors were located at 5, 10 and 15 m after the end of the vegetation. The supporting rods were prepared to hold two sensors. The sensors were located 2 and 4 m from the soil (Fig. 3). The normal of their sensing area was horizontally oriented in order to measure incident heat fluxes emitted by the flame front. The sensors used incorporate balanced thermoelectric panels housed between copper foils which provide low response time lower than 0.5 s. Each of these hemispherical sensors is composed of different sensing areas (squares of 1 cm^2) set on a heat exchanger (Fig. 3). A sensor allows to measure the radiant and total heat fluxes. The convective heat flux is deduced by subtracting the total heat flux and the radiant one. The heat flux sensors have a useful range from 0.1 to 100 kW/m^2. The calibration of the sensors was done by submitting them to reference heat fluxes. Based on manufacturer's data, the standard uncertainty for the heat flux measurements is estimated at ±3 %. The sampling rate was 1 measurement per second per sensor.

2.4 Anemometers and weather station

Three two-dimensional ultra-sonic anemometers were placed around the plot. These anemometers, which have a low response time, accept sampling rate of 1 measurement per second and allowed to record the important variations in wind speed or direction at a height of 2 m from the ground. They were located at 10 or 20 m from the plot (Fig. 1).

An automatic weather station was also installed in the study area two months before the experiments in order to record the local meteorological conditions [31]. The weather station equipped with air temperature, relative humidity, wind speed and direction sensors was located downslope the plot (Fig. 1). The measurements were done 3 m above the ground level. Averaged data were acquired every minute.

2.5 Infrared camera

The flame front was recorded with an infrared camera (CEDIP, Jade3MW) operating in the MIR band (from 3 to 5 μm). The camera has a 256 × 256 focal plane array and infrared images were stored on a PC with a 14 bits resolution. The acquisition rate was 25 images per second. In order to obtain measurements of the characteristic length scales of the flame front, the camera was facing the vegetation plot. It was located at 30 m from the vegetation/firebreak interface (Fig. 1). During combustion process in the gaseous phase, the major part of the products emits radiation in the infrared region and more intensively in the 4.3 μm band. The camera, using a filter for CO_2 species (specified wavelength near 4.3 μm), was focused on the measuring section. At that distance, a pixel represents an area of about 0.16 m^2. The emissivity of reacting medium such as flame is not easy to determine thus the images obtained were not calibrated. Only qualitative measurements of characteristic length scales of the buoyant diffusion flame front were done, using a processing technique of infrared images [14]. This technique allows to determine the limits between three regions: the continuous flame, the intermittent flame and the plume regions.

2.6 Video camera

In order to help to obtain accurate observations, three digital video cameras recorded images (25 images/sec) of the fire from the side and front view (Fig. 1). The cameras were located at about 25 m from the vegetation and focused on the thermocouples supporting rods. The video recordings provide information on the flame geometric properties, namely the flame height and tilt angle. The luminous flame height is defined perpendicularly to the terrain. The flame tip is considered to be attached to the flame. The flame tilt angle is defined as the angle between the vertical direction and the leading surface of the flame. The average flame characteristics were computed every 5 s. Another video camera was placed in a high location in order to localize the fire front during its spread across the vegetation.

3. Results and discussion

In the first place, the wind measurements done during the fire spread are analysed and the wind characteristics are discussed. Then, the effects of the wind fluctuations on the fire spread as well as the flame shape, temperature and radiation emission, are investigated.

3.1 Wind characteristics

The instantaneous components of the wind, namely the velocity, u and the direction, θ, recorded by each anemometer, can be decomposed into an averaged and a fluctuating part, as follows:

$$u(t) = U + u'(t) \quad (1)$$

$$\theta(t) = \Theta + \theta'(t) \quad (2)$$

The mean and fluctuating quantities for each anemometer, are provided in Table 2. The measurements exhibit spatial and temporal variation of wind characteristics over the plot since the wind is influenced by the topography of the terrain, the vegetation and the fire itself.

The velocity field is commonly presented in Cartesian coordinates. Aligning the longitudinal direction of a Cartesian system (x, y) with the mean wind direction Θ, the wind can be expressed according to a longitudinal and transverse components, as follows:

$$u_x(t) = u(t)\cos(\theta(t) - \Theta) \quad (3)$$

$$u_y(t) = u(t)\sin(\theta(t) - \Theta) \quad (4)$$

The decomposition, into average and fluctuating parts, allows to observe the turbulent nature of the wind velocity field through its longitudinal and transverse components. The autocorrelation functions S_{xx} and S_{yy}, associated to fluctuating velocity component $u_x'(t)$ and $u_y'(t)$ respectively, reveals the nature of turbulence in the surface layer. These quantities represent the longitudinal and the transverse components of turbulent kinetic energy, namely the kinetic energy of wind fluctuations. The spectral densities of the velocities fluctuations E_{xx} and E_{yy}, as a ratio to the local mean speed squared are provided in Fig. 4 against reduced frequency $f_{red} = f\frac{z}{U(z)}$ for a height z of 2 m. These spectra are computed for the fire spread duration using a Fast Fourier Transform with an

4096 point Hanning window, for a sampling frequency Fs equal to 1 Hz. These spectra are close to those found in the literature [33-35] and behave as $f^{-\alpha}$, with α positive. In the present study two values of α can be fitted, each of them defining a different behaviour. In the first region, found between the frequency range from 6.10^{-4} to 10^{-1} Hz, α is about 0.6. In the second region, the determination of α is more difficult because of the lack of data close to the upper frequency limit Fs/2 imposed by the Shannon theorem. However, α seems to fit a value larger than 5/3, the Kolmogorov exponent. According to previous works done on the airflow through vegetation canopy [36-37], frequencies in this second range sign phenomena dominated by strongly dissipative processes of turbulent kinetic energy. This dissipation is mainly due to the drag induced by the flow through the vegetation. The first region is related to velocity fluctuations occurring on periods from the ten to the hundred seconds. The time scales associated with this range, due to a mean wind velocity of about 4.2 m/s and a standard deviation of about 2 m/s, coincide with large lengths about few hundred meters [33-34]. These length scales, close to those of the experimental site, originate from the topography of the upward terrain where the wind flows. The change of slope, delimiting two spectral regions, occurs at a reduced frequency of 10^{-1}. The first region is governed by the large scale wind fluctuations; while the second one is due to wind fluctuation at small scales caused by the wind flow through the vegetation. This frequency is used for filtering the acquired data of wind, u and θ with a low-pass Butterworth filter 4th order. In this procedure, the higher velocity fluctuations are filtered out. Instantaneous and filtered wind velocity and direction at a height of 2 m measured with anemometer 1, located at the right hand side of the plot, are provided in Fig. 5. This process makes the slow wind variations of wind, which are essentially due to the wind flow through terrain topography, stand out and allows a better readability of the wind measurements too. The filtered signal excludes the dissipative effects caused by the canopy. The effects of these wind fluctuations on the fire spread as well as the flame shape, temperature and radiation emission, are investigated in the following.

3.2 Fire behaviour

The fire spread experiment was conducted on July 2 at 16h33 under conditions of clear sky (air temperature: 28°C; air relative humidity: 53%) and moderate wind (about 4.2 m/s). As a first step, a line-ignition attempt was made at the beginning of the plot but fire went out. A point ignition was then performed at the right side of the flat part of the plot were the vegetation was drier. Nevertheless, the high fuel moisture content resulted in a difficult fire spread which produced a thick smoke plume. The fluctuating wind caused very pulsating flames with masses of hot gases which frequently separated from the main flame front. The history of the fire front perimeter, obtained from both video recording and thermal fuses information, is provided in Fig. 6. The symbols represent the location of the thermocouples (circles) and the heat flux sensors (squares). The sensors, which measurements will be discussed in the following, are represented in black.

The fire front travelled about 18 m along the wind direction (west) and established a pointed-shaped head. The fire spread was mainly governed by the wind velocity fluctuations (Fig. 5.a). Due to the high fuel moisture content, the fire spread when the wind velocity was greater than a threshold value (about 3 m/s). After about 4 min (time 2280 s), the fire front turned and travelled about 5 m along the south-west direction. The wind direction was about constant (269°) during the fire spread (Fig. 5.b) and this fire behaviour was attributed to the vegetation heterogeneity. At time 2280 s, the fire front was stopped by a grove of *Olea europa* and spread into *Arbutus unedo* and *Cistus monspeliensis*. The flame front reached the vegetation/firebreak interface about 6 min after ignition (Fig. 7). The burned area was about 110 m^2. The fire did not achieve a steady state because of the combined effects of wind shift and vegetation heterogeneity. During these two steps, the rate of spread ranged between 0.1 and 0.4 m/s. The whole vegetation of the plot did not burn out and another fire spread, ignited by glowing embers occurred in the unburned vegetation on the left side of the plot when wind got stronger [31]. The results provided in the following concern the first fire spread across the centre of the plot.

The analysis of the video and infrared recordings, when the fire entered in the measuring section, put to the fore the following features. The wind-blown fire travelled faster in the upper part of the vegetation layer than in the lower one. The most abundant species in this region were *Quercus ilex* and *Arbustus unedo* for the high stratum and *Cistus monspeliensis* for the low stratum. It should be noticed that the fuel moisture content of the vegetation was greater for the low stratum. Furthermore, the heat transfer processes in the upper part of the vegetation are greater due, to flame radiation impinging upon the vegetation top and direct flame contact caused by the gusts of wind. The fire spread across the upper layer of the vegetation, was followed by a second one across the lower stratum. The vegetation of the lower stratum was sufficiently dried by the fire in the high stratum for the fire to spread there.

3.3 Flame front geometry

The processing of the infrared images, allows to measure the characteristic length scales of the flame for the two fire spread events. This technique [14] was applied to about 400 and 700 images of the fully developed buoyant diffusion flame when the fire was in the measuring section. The intermittencies of both flame fronts, which represents the flame presence probability contours, are provided in Fig. 8. The continuous flame length, L_c and the maximum flame length, L_m are defined as the distance, from the base of the flame, at which the flame intermittency is 0.95 and 0.05, respectively. The continuous flame region is found below L_c, the intermittent region is found between L_c and L_m and the plume region is found above L_m. The average flame height, L_f is defined as the height for which intermittency is 0.50. The value of the characteristics length scales, for both fire spreads in the different vegetation layers, are provided in Table 3. It should be noticed that the structure of the flame at field scale differs from the one encountered at laboratory scale [14]. In particular, for both fire spreads the intermittent flame region was larger than the one measured in the previous works in the laboratory. This could be due to the effects of the wind and the properties of the vegetation but more experimental fires are required to confirm this result. The ratio of the continuous flame height to the maximum flame height is lower than 0.25. The intermittent flame represents here about 75% of the maximum height of the flame and it represented only 55% in earlier study at laboratory scale.

During the experiment conducted in presence of wind, the flame front was carried downstream from the fire. The flame tilt angles were obtained from video recording analysis of the side view. The flame tilt angle exhibits great variations over time caused by the wind velocity fluctuations (instantaneous signal on Fig 5.a), thus the flame tilt angle was only computed when the fire was in the measuring section (between 2330 and 2500 s). The mean tilt angle for the fire spread in the upper part of the vegetation was 35 ± 9 °. The flame tilt angle was difficult to measure for the fire spread in the lower part of the vegetation since the flame did not exceed the vegetation height. Nevertheless, observations showed that wind did not penetrate inside the vegetation layer and the flame was less tilted.

3.4 Flame front temperature

The two flame fronts travelled through the vegetation layers and reached the thermocouple supporting rod, located at the centre of the plot (black circle on Fig. 6), at time 2270 and 2360 s, respectively. The temperature-time curves for three thermocouples located inside the vegetation (which heights above the soil are 0.6, 1.2 and 2.4 m) and three thermocouples located in the flame (which heights above the soil are 2.4, 3.6 and 4.8 m) are provided in Fig. 9. As far as the measurements inside the vegetation are concerned (Fig. 9.a), the temperature raise occurred in a first place for the thermocouple 4 located at the top of the shrub layer (2.4 m). Thus, the temperature measurements inside the vegetation layer confirm the spreading of two successive fires in the higher and lower vegetation stratum. The residence-time of the fire at the top of the vegetation is about 50 s. A second fire spread in the lower part of the vegetation, occurs 40 s later with a greater residence time (about 200s). These measurements exhibit temperatures which are in the order of magnitude of the one measured during laboratory scale experiments, but the fire had a greater residence time. Moreover, the temperature measurements above the vegetation (Fig. 9.b), show that the flame front was tilted by the wind. The delay between the increase of temperature of the thermocouples 8 and 4 spaced 2.4 m is about 20 s. The temperatures fluctuations are mainly due to the gusts of wind which tilted the flame front and are discussed hereafter.

The thin thermocouples used, with 50 μm wire diameter, allow to record the fluctuations of the temperature when the flame front was in the measuring section. The frequency content of the temperature curves for two thermocouples is provided in Fig. 10.a. These normalised power spectrums were computed on 4096 informative points with a Fast Fourier Transform algorithm. The spectral analysis of the temperature curve, recorded by the thermocouple 6 located about 1 m above the vegetation, reveals characteristic frequencies located between 4 and 6.10^{-3} Hz and between 10 and 13.10^{-3} Hz. These low frequencies are caused by the fire spread in the lower and upper strata of the vegetation respectively. Indeed, the same process applied to the thermocouple 1 located inside the vegetation (0.6 m from the ground), reveals only a characteristic frequency in temperature fluctuations of 4.10^{-3} Hz. The characteristic durations associated to these low frequencies are about 200 and 80 s respectively and correspond to the residence time of the flame in these strata. The higher frequencies in temperature fluctuations appear to be caused by the gusts of wind. The frequency content of wind velocity and temperature curves (for the thermocouple 6 located above the vegetation), between 3.10^{-2} and 11.10^{-2} Hz, is provided in Fig. 10.b. The wind speed was taken from the anemometer 1, located at the right side of the plot, which is not influenced by the fire and the generated smoke. These results show that the frequency content of the temperature and wind velocity exhibit similarities within this frequency range. The temperature and wind velocity seems to be correlated and the characteristic duration of the gusts of wind, which affect the temperature, range from 10 to 30 s. It should be noticed that the effect of wind on temperature fluctuations is less significant for the thermocouples located inside the vegetation. The wind hardly penetrates inside the vegetation which confirm the fact that the flame was less tilted during the second spread.

The maximum temperatures along the vertical direction, for both fire spreads, are provided in Fig. 11. The circles represent the maximum temperature measured during the first fire spread between 2250 and 2350 s. The triangles represent the maximum temperature measured during the second fire spread between 2350 and 2550 s. The average temperature during these periods will not be given here. The flames were tilted by the wind and providing average quantities during both periods makes no sense. Indeed, all the thermocouples were not inside the flame during the same moments and averaged values during the whole period are not representative. These temperature profiles effectively exhibit that the fire brunt at the first time the upper part of the vegetation since the maximum temperatures measured below 1.8 m high during the first fire spread were always lower than the ignition temperature of vegetal fuels (about 300°C). In connection with the measurement of the characteristic length scales of the flame (Table 3), the continuous flame corresponds to maximum temperature greater than 800°C. The maximum flame height corresponds to maximum temperature of about 500°C. The plume region is found above 500°C.

3.5 Flame front radiation

The measurement of the thermal radiation emitted ahead of the flame front is of great interest for the understanding of the fire spread behaviour, the models validation, the fire-fighters security or the proportioning of the wildland/urban interfaces. The radiation emitted from the fire front play a significant role in the preheating of the vegetation during the fire spread. When the flame front reached the vegetation/firebreak interface (Fig. 7), the sensors located along the second raw (black squares on Fig. 6) were exposed to the greater heat fluxes. The radiant heat flux versus time for the sensors placed at 5, 10 and 15 m from the vegetation edge (2 m above the soil) are provided in Fig. 12. As the flame front spread and got closer to the sensors, the radiant heat flux increased. The sensors located at 4 m high gave similar measurements. The hemispherical sensors measured jointly the heat fluxes from flame and combustion zones. The comparison between radiant and total heat fluxes measurements show that convection incident beyond 5 m ahead of the flame front is negligible and will not be discussed here. In this study, radiation appears to be the dominant heat transfer mechanisms involved in the long-range preheating process of the vegetation. Indeed, the smoke temperature at the level of the sensors was about 10 °C above ambient and convective heat flux was not significant.

Because of the two-steps fire spread, the radiant heat fluxes measured during this experiment were less significant than if the fire burnt out the whole vegetation in one go. The radiant heat flux measurements at 5 m from the flame front, for the two fire spreads ranged from 4 to 8 kW/m² and from 2 to 4.5 kW/m², respectively. The flux measured during the first spread was greater due to taller flames (Table 3). The peak at about 8 kW/m² is attributed to a gust of wind (Fig. 5.a) which fan the fire and tilted more the flame front. The curves of the radiant heat flux are naturally correlated to the ones of the thermocouples. The spectral analysis of the heat flux curves reveals the same lower characteristic frequencies as those contained in the temperature fluctuations, namely 5.10^{-3} and 15.10^{-3} Hz. These two frequencies correspond to the spread of the fire in the high and low strata of the vegetation. Moreover, the frequency content of the radiant heat flux also exhibits great similarities with the one of the wind. These results suggest the radiative transfers are also strongly influenced by wind because of its effects on flame properties and combustion rates. However, more experiments under a wide range of wind conditions are essential to further study this interaction between turbulent wind and radiation.

4. Conclusion

A first experiment was conducted in the field by the university of Corsica team in order to collect valuable data on the fire front spread at that scale. This study showed that it was possible to measure thermodynamic quantities in the field since the wind characteristics, the flame front temperature and radiation were recorded successfully. However, the fire was conducted across shrubs after an exceptional rainy period for the season which resulted in a difficult fire spread governed by the wind. The future experiments should be preferentially conducted across a more homogeneous vegetation or with a line ignition in order to avoid the significant effects of the vegetation on fire spread. The results showed that the fire travelled across the shrubs with a two-step process. In a first place, the fire burned the upper layer of the vegetation. This fire was followed by a second fire front within the lower layer. As a result, the fire intensity was not as greater as expected. This behaviour of the fire, very different from the one encountered during fire spread across fuel beds at laboratory scales, put to the fore the necessity to consider field scale experiments for the validation of the fire spread models at that scale. Of particular interest is also the change of the flame structure character observed in the field. The flames are composed of three regions (continuous, intermittent and plume) but their structure differs from the one encountered at laboratory scale because the intermittent region was larger. The temperatures measured within the flame front in the field were in the order of magnitude of the ones measured during laboratory scale experiments but the fire had a greater residence time. The heat fluxes measurements showed that radiation was the dominant long-range mechanism of preheating ahead of the fire front; but the sensors were located too far away from the fire to determine which heat transfer process contributes for the major part of the heat required to fire spread. The future experiments would benefit from the use of others sensors (heat flux sensors inside the vegetation) to investigate these mechanisms involved in fire spread at field scale. As far as the wind is concerned, the large scale turbulence played a significant role on fire spread since it affected the flame shape, temperature and radiation emission. The whole results are encouraging but more experimental fires must be conducted in the field to further assess this wind/fire interaction.

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Table 1. Measured quantities during fire experiments conducted in the field

Author	Plot area	Vegetation type	Measurements
Carrega (2002)	100 m x 200 m	moor	- meteorological conditions (wind 2 to 7 m/s) - fire rate of spread (0.7 m/s)
De Luis et al. (2002)	33 m x 33 m	shrub fuel height: up to 1.25 m fuel load: 2.8 to 4.5 kg/m^2	- vegetation characteristics - meteorological conditions (wind 0.3 to 0.9 m/s) - soil temperature - fire rate of spread (0.01 to 0.03 m/s)
Cheney and Gould (1993, 1995)	ranging from 100m x 100m to 200m x 300m	grass fuel height: 0.1 to 0.6m fuel load: 1 to 6 t/ha	- meteorological conditions (wind 2 to 7 m/s) - fire rate of spread (0.25 to 2 m/s) - fire front shapes (aerial photography)
Viegas et al. (2002)	ranging from 50 x 50 to 100m x 165m	shrub fuel height: 0.6 to 1.6m fuel load: 1.3 to 11 kg/m^2	- meteorological conditions - topography (slope 11 to 32°) - fire rate of spread - fire front shape (infrared and video imaging) - smoke analysis
Santoni et al. (2005) and present work	30 m x 80 m	shrub fuel height: up to 2.5 m fuel load: 10 kg/m^2	- vegetation characteristics - vegetation cartography - meteorological conditions (wind 4.2 m/s) - topography - fire rate of spread (0.1 to 0.4 m/s) - flame geometry - radiant heat flux (up to 8 kW/m^2) - fire plume temperature - smoke analysis - infrared and video imaging
Cohen (2000) and Alexander et al. (1998)	ranging from 75 x 75 m to 150 x 150 m	forest fuel height: 13 m fuel load: 3500 pines/ha	- vegetation characteristics - meteorological conditions - fire rate of spread - flame geometry - radiant heat flux - gas temperature - smoke analysis - infrared and video imaging

Table 2. Wind characteristics measured during fire spread.

	Average wind velocity (standard deviation)	Average wind direction (standard deviation)
Anemometer 1	3.80 m/s (1.78)	267 ° (27)
Anemometer 2	4.36 m/s (1.60)	266 ° (20)
Anemometer 3	4.04 m/s (1.74)	271 ° (23)

Table 3. Characteristic length scales of the flame front measured in upper and lower strata.

	Height of the flame base	Continuous length, L_c	Mean length, L_f	Maximum length, L_m
Upper stratum	0.7 – 1.8 m	2.3 m	4.0 m	7.2 m
Lower stratum	0.0 m	0.7 m	1.3 m	3.0 m

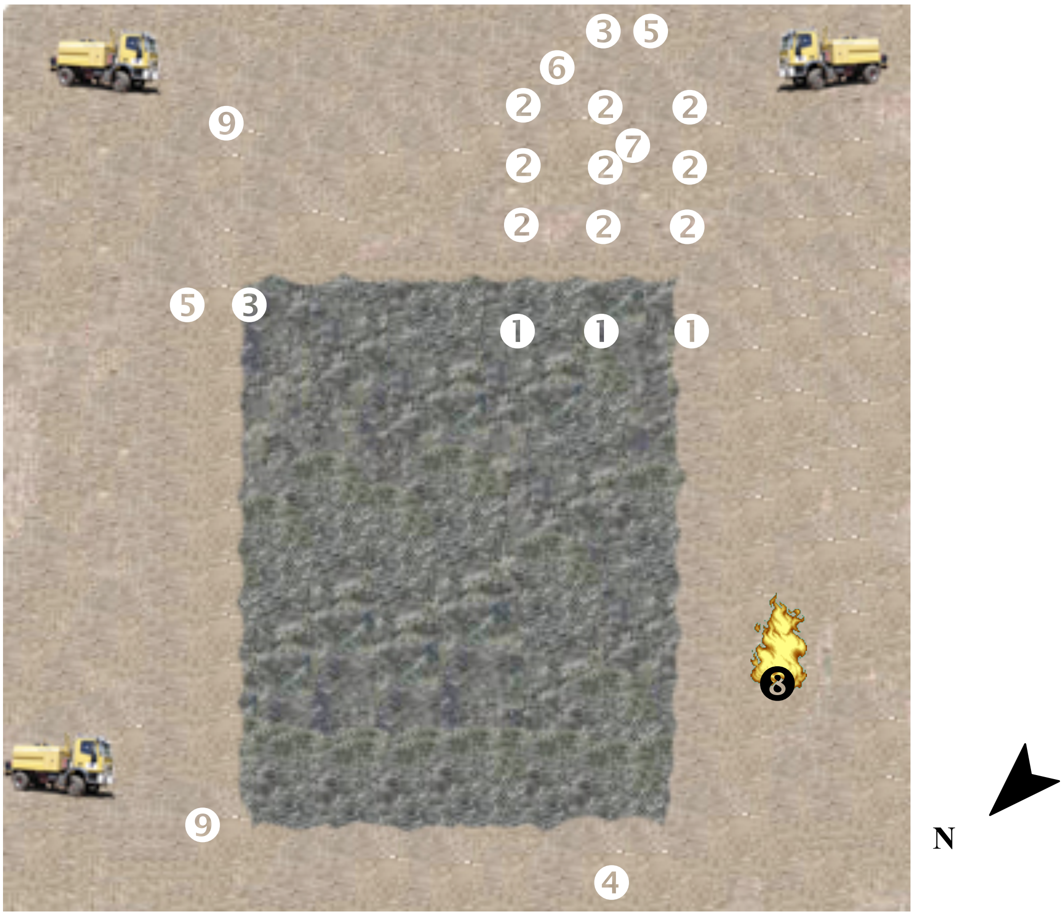


Fig. 1. Schematic of the experimental device. Fig. caption: 1: thermocouples, 2: heat flux sensors, 3: anemometers, 4: weather station, 5: video cameras, 6: infrared camera, 7: data logger, 8: point ignition, 9: fire fighting vehicles.

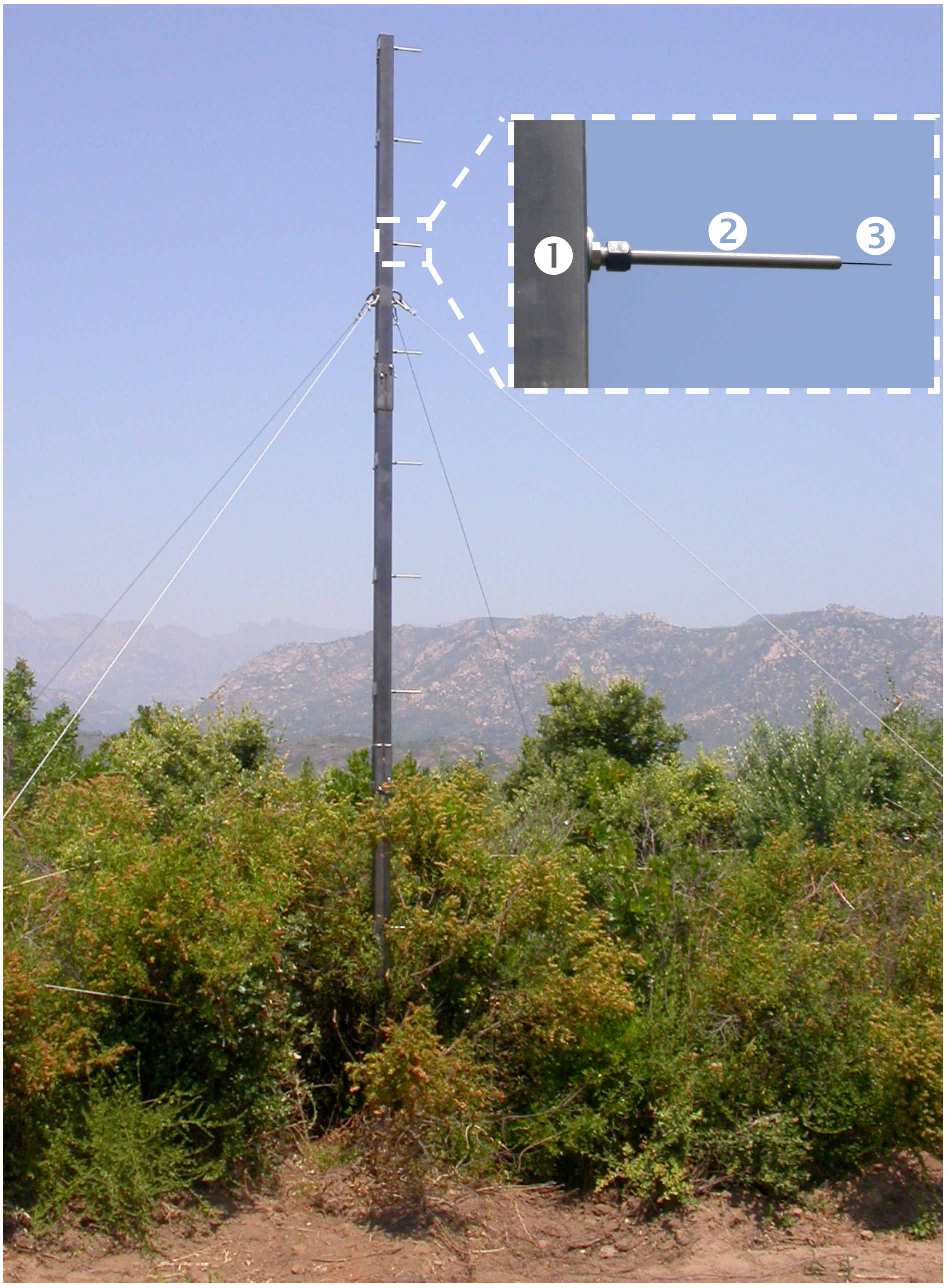

1
2
3

Fig. 2. Photograph of a thermocouples supporting rod. Figure caption: 1: supporting rod, 2: stainless steel tube, 3: thermocouple (magnified).

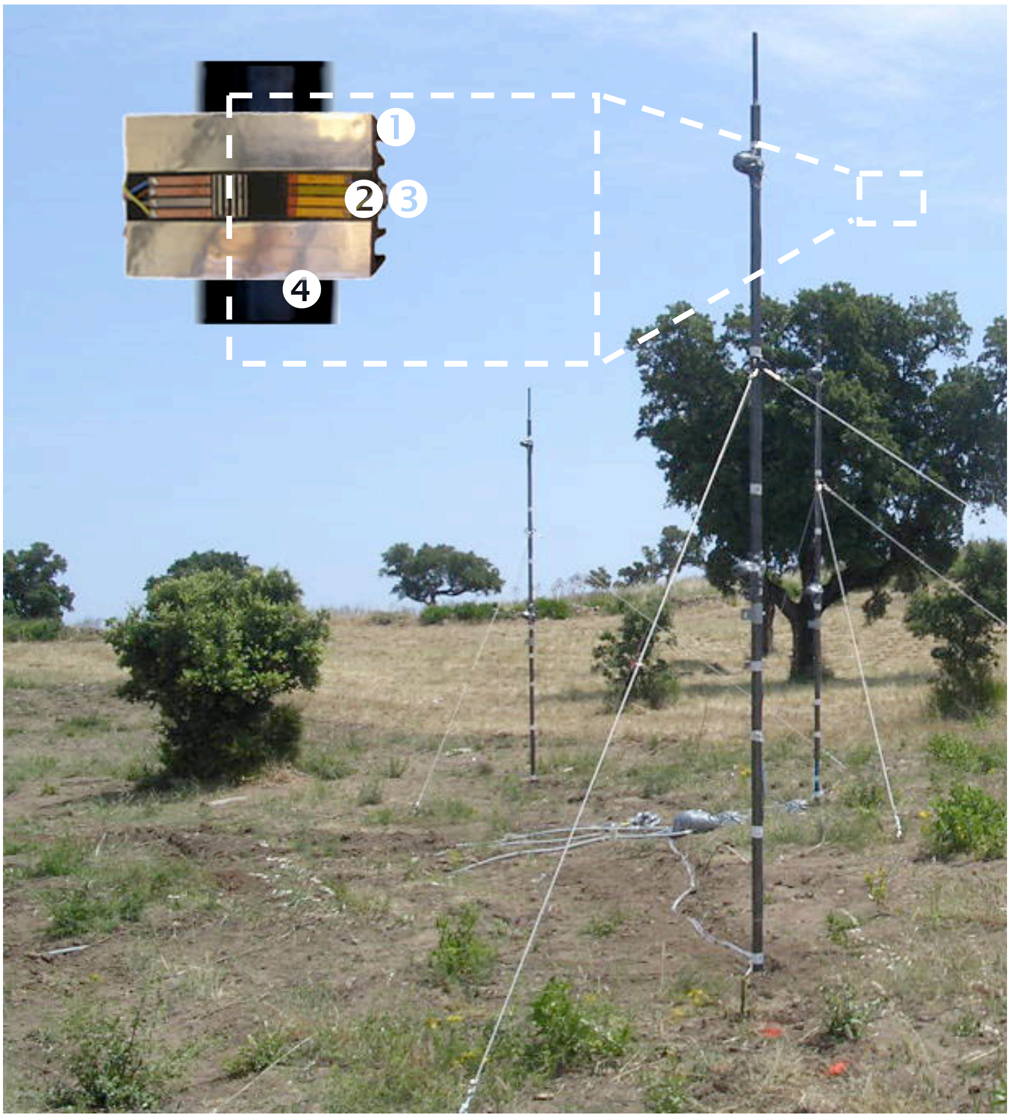


Fig. 3. Photograph of a heat flux sensors supporting rod. Figure caption: 1: rod, 2: radiant heat flux sensitive area, 3: total heat flux sensitive area, 4: heat exchanger.

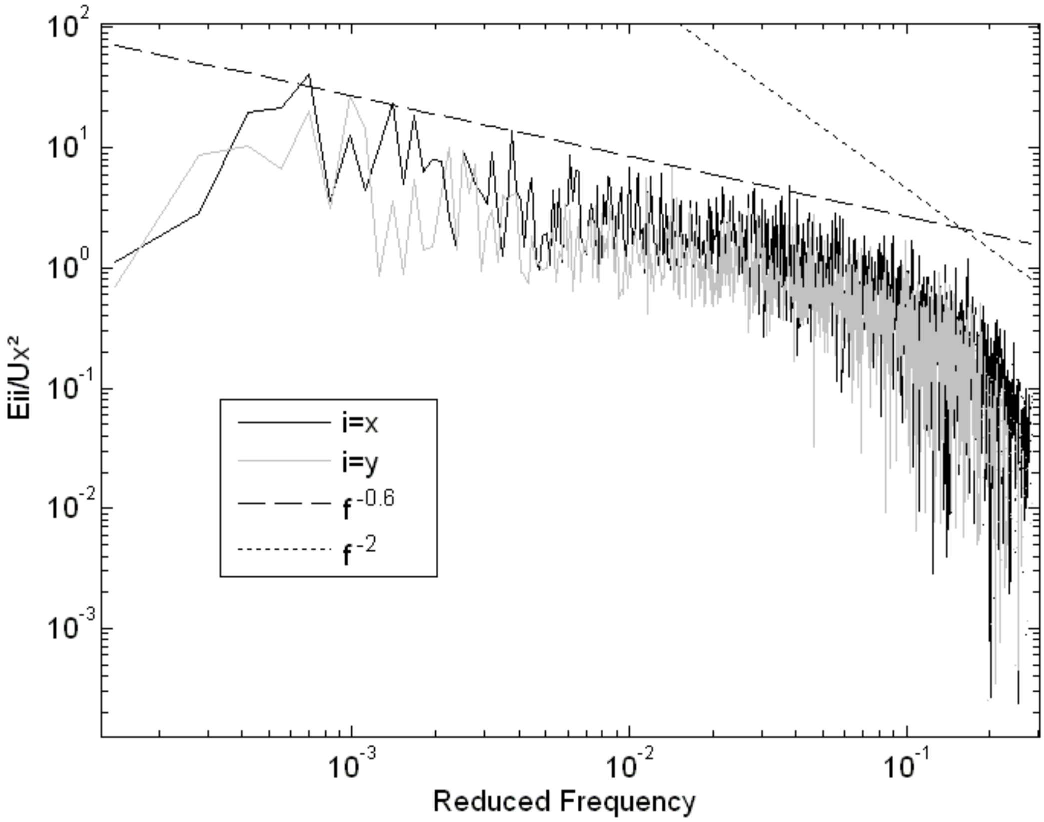


Fig. 4. Two-component turbulence spectra at a height of 2 m.

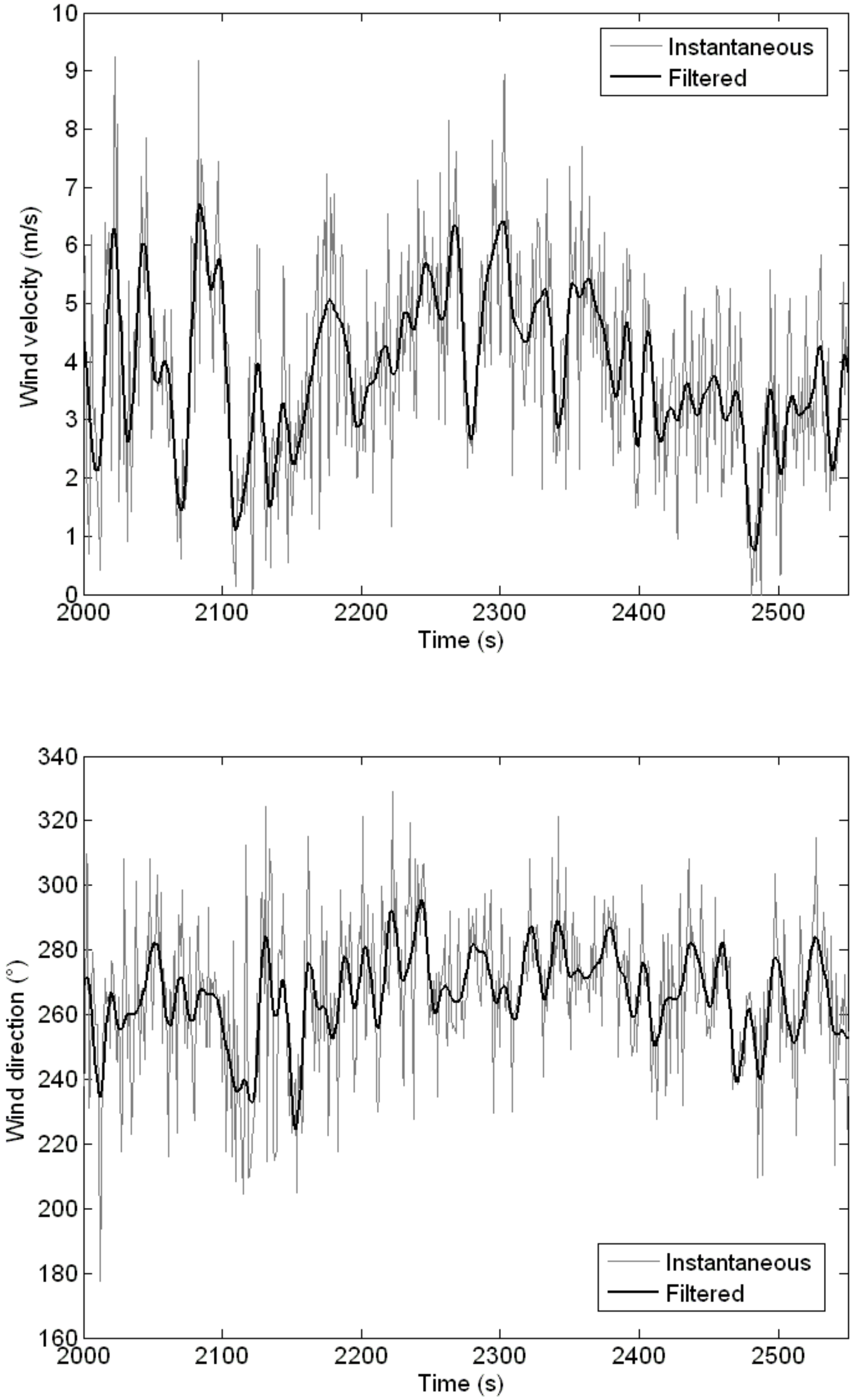


Fig. 5. Instantaneous and filtered wind characteristics (a) velocity and (b) direction.

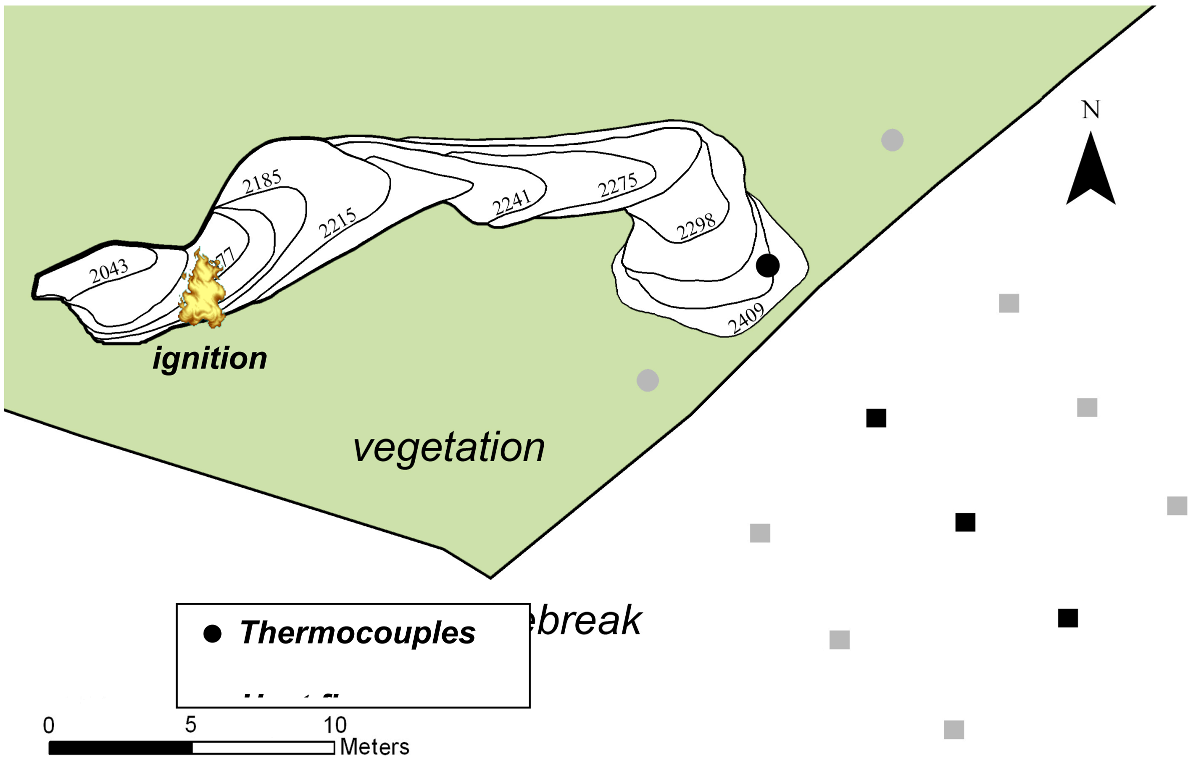


Fig. 6. History of the fire spread across a Mediterranean shrub. The isochrones represent the fire front perimeter and numbers indicate the time (s).

Fig. 7. Photograph of the fire experiment about 6 min after ignition.

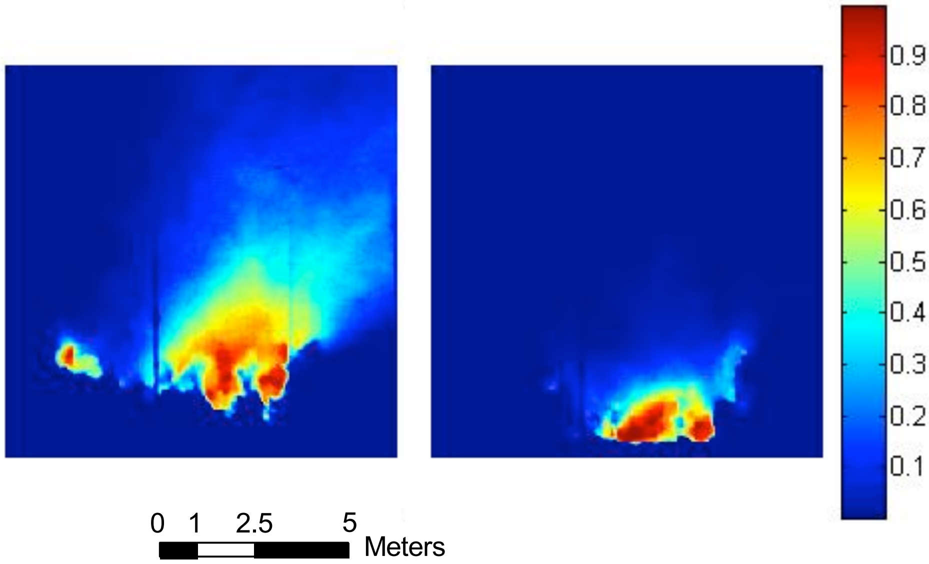
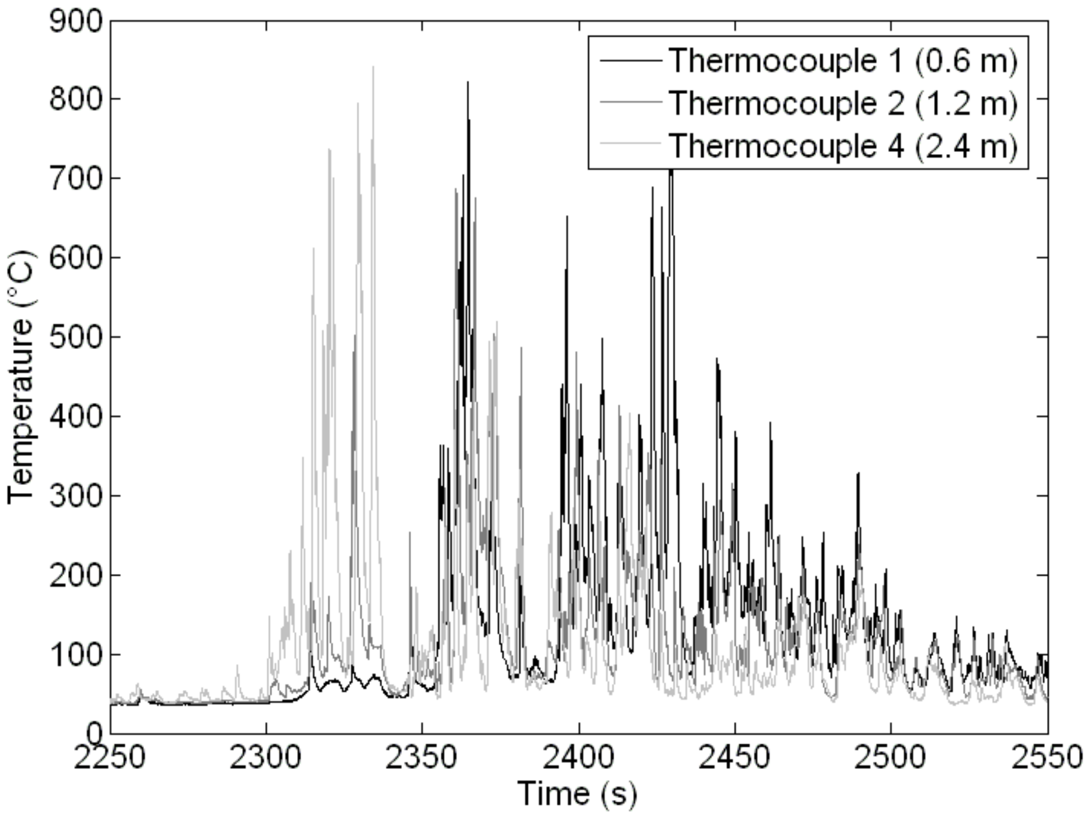


Fig. 8. Intermittency of the flame front for fire spread (a) at the upper and (b) lower part of the vegetation.


Thermocouple 1 (0.6 m)
Thermocouple 2 (1.2 m)
Thermocouple 4 (2.4 m)
Temperature (°C)
Time (s)
0
100
200
300
400
500
600
700
800
900
2250
2300
2350
2400
2450
2500
2550

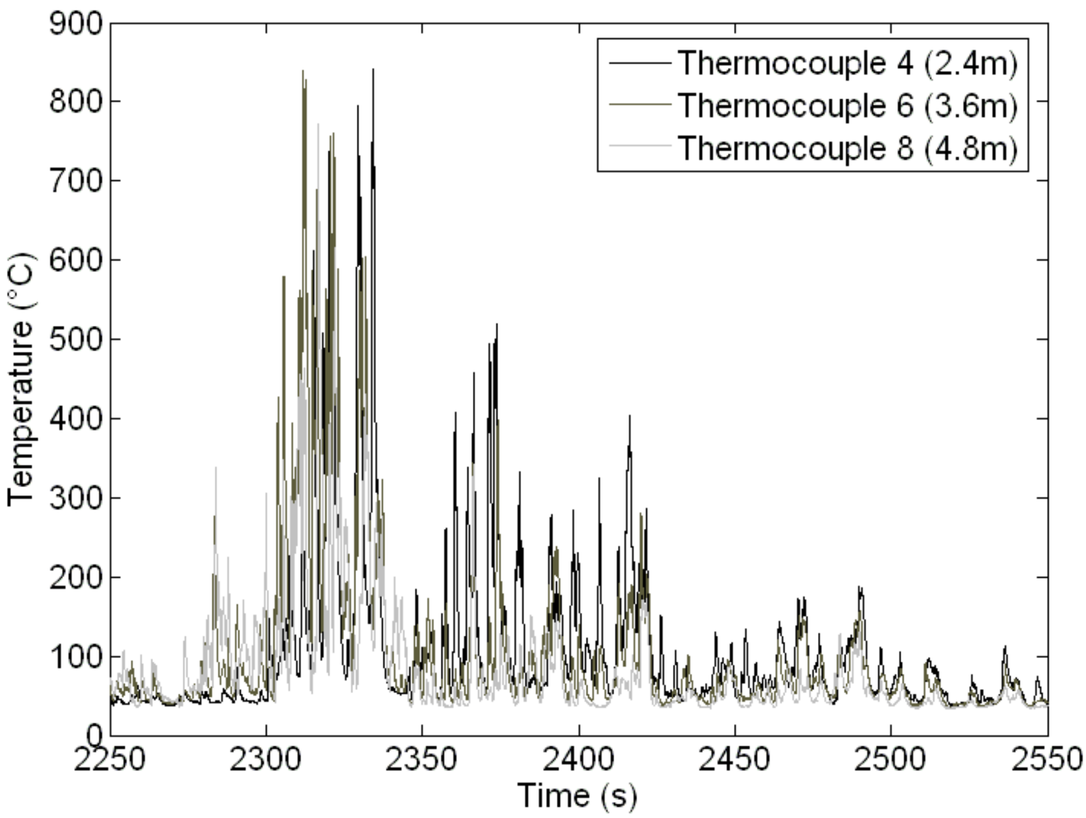
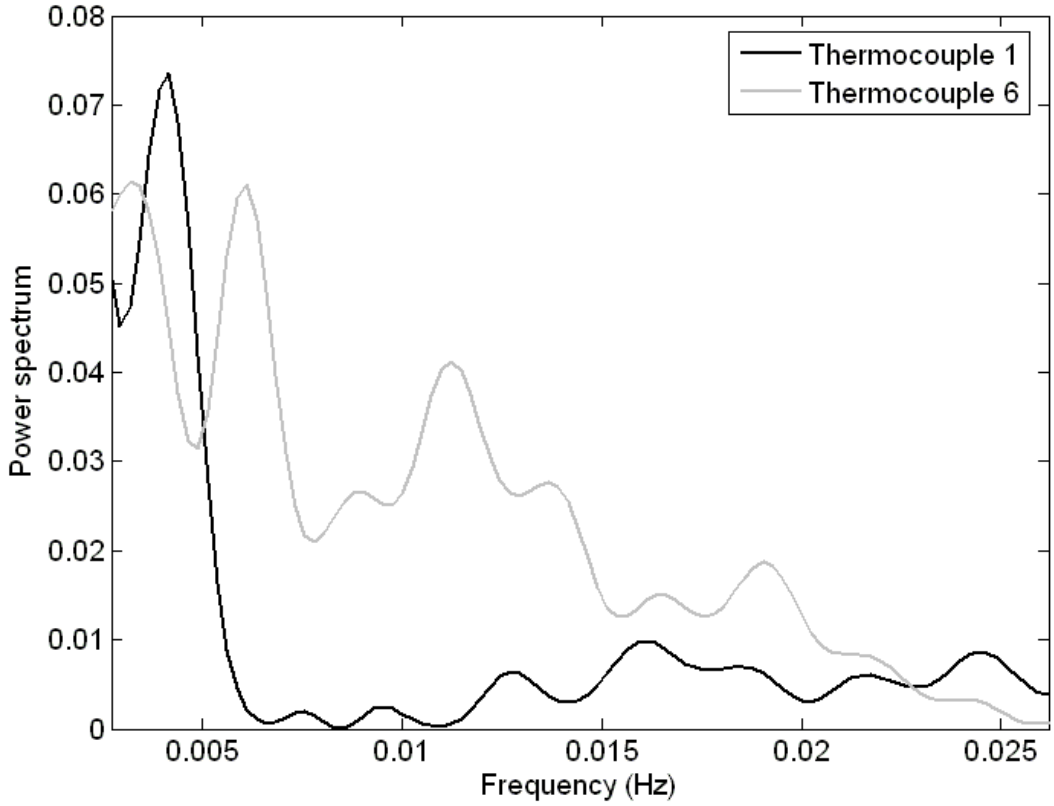

Thermocouple 4 (2.4m)
Thermocouple 6 (3.6m)
Thermocouple 8 (4.8m)
Temperature (°C)
Time (s)
0
100
200
300
400
500
600
700
800
900
2250
2300
2350
2400
2450
2500
2550

Fig. 9. Temperature-time curves recorded at different height (a) inside and (b) above the vegetation.


Thermocouple 1
Thermocouple 6
Power spectrum
Frequency (Hz)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.005
0.01
0.015
0.02
0.025

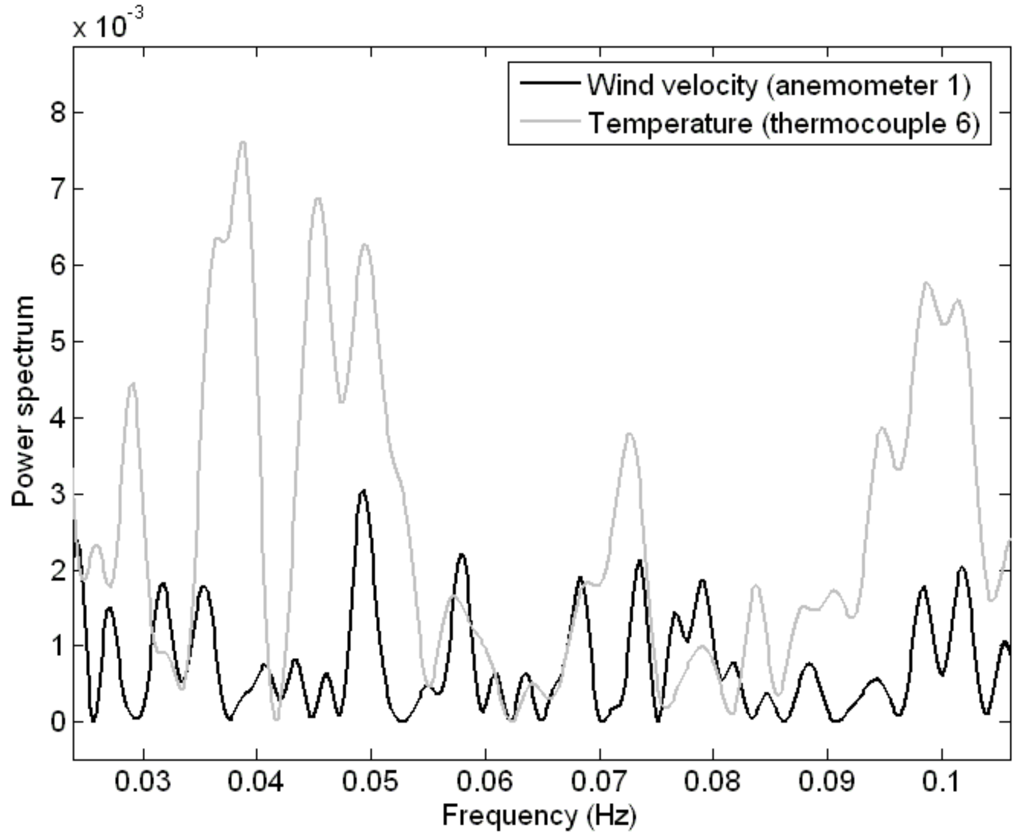

x 10-3
Wind velocity (anemometer 1)
Temperature (thermocouple 6)
Power spectrum
Frequency (Hz)
8
7
6
5
4
3
2
1
0
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

Fig. 10. Frequency content of (a) temperature for thermocouples 1 and 6 between 0 and 0.025 Hz and (b) temperature for thermocouple 6 and wind for anemometer 1 between 0.03 and 0.1 Hz.

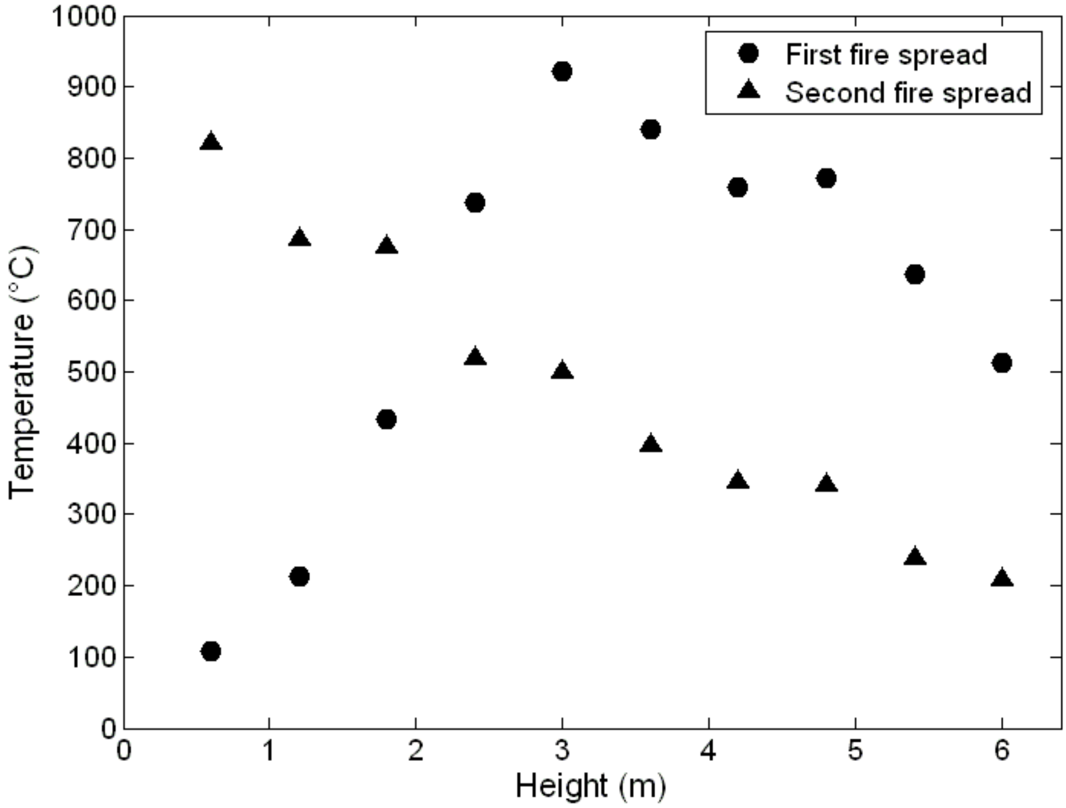


Fig. 11. Maximum temperature versus height measured during the first fire spread across the upper stratum (between 2250 and 2350 s) and the second fire spread across the lower stratum (between 2350 and 2550 s).

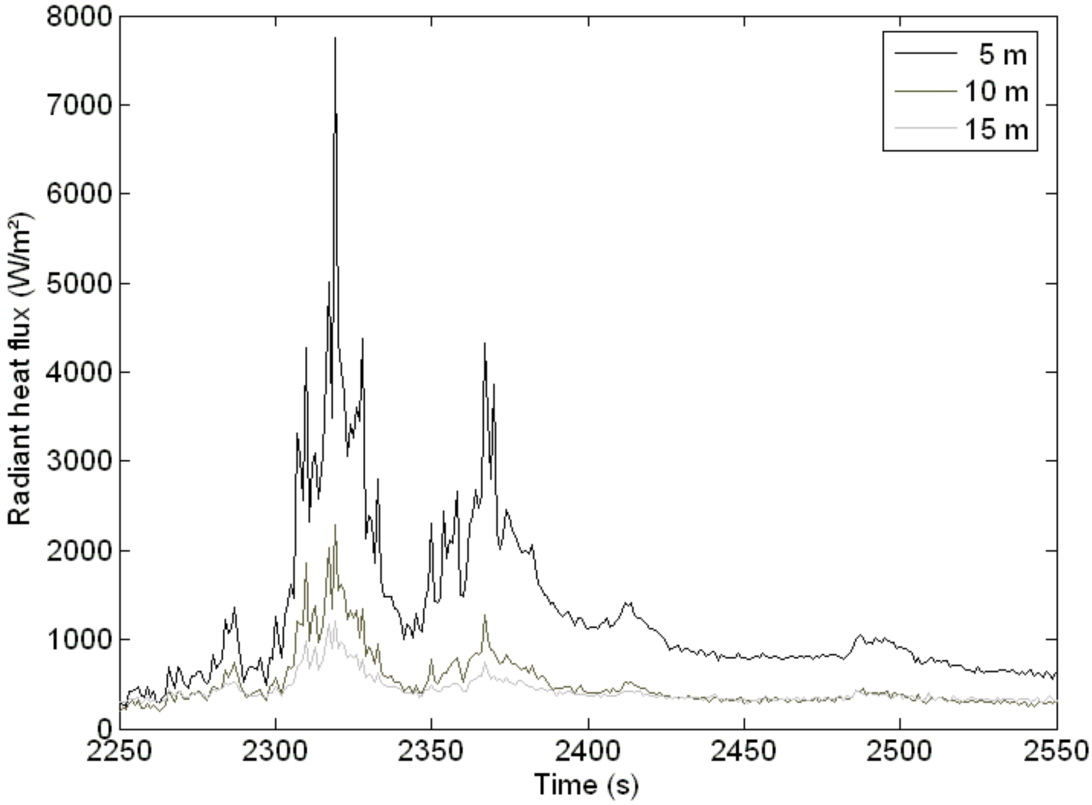


Fig. 12. Radiant heat flux versus time curves recorded at 5, 10 and 15 m from the flame front.