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1 **Experimental investigation of the physical mechanisms governing**
2 **the spread of wildfires**

3
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5
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10
11 **Abstract**

12 One of the objectives of the present study is to gain a deeper understanding of the heat
13 transfer mechanisms that control the spread of wildfires. Five experimental fires were
14 conducted in the field across on plots of living vegetation. The lengths of the ignition lines
15 were set in the range of 20–30 m to reproduce wildfire front conditions as closely as possible.
16 The experiments were performed under various vegetation properties, wind conditions and
17 plot topography to highlight different fire spread behaviours. This study focused on
18 characterising heat transfer ahead of the flame front. The temperature and heat flux were
19 measured at the top of the vegetation as the fire spread. The results showed the existence of
20 two different fire spread regimes that were either dominated by radiation or governed by
21 mixed radiant-convective heat transfer. For plume-dominated fires, the flow strongly responds
22 to the great buoyancy forces generated by the fire; this guides the fire plume upward. For
23 wind-driven fires, the flow is governed by inertial forces due to the wind, and the fire plume
24 is greatly tilted towards unburned vegetation. The correlations of the temperature (ahead of
25 the flame front) and wind velocity fluctuations change according to the fire regime. The
26 longitudinal distributions of the radiant heat flux ahead of the fire front are also discussed.
27 The data showed that neither the convective Froude number nor the Nelson convection

28 number—used in the literature to predict fire spread regimes—reflect the observed behaviour
29 of wind-driven fires.

30 *Keywords:* wildfires; field experiments; temperature; heat transfer; radiation.

31

32

33 **Introduction**

34 Experimental fires have been widely used in fire research to further our understanding of the
35 complex mechanisms governing the behaviour of fires. A large number of experiments have
36 been carried out at the laboratory scale to study fires propagating across fuel beds (Dupuy
37 1995, Mendes-Lopes *et al.* 2003, Viegas *et al.* 2004). These reduced-scale experiments allow
38 the observation of the main features encountered in wildfires and even some specific
39 behaviour such as eruptive fire (Viegas 2006). However, fire is a scale-dependent process
40 (Pitts 1991), and studying a fire as it spreads under full-scale conditions appears more
41 relevant than across small fuel beds. Indeed, flame front properties (height, irradiance, etc.)
42 and the resulting heat transfer mechanisms in the laboratory are not of the same order of
43 magnitude as those in the field. In a previous work (Silvani and Morandini 2009), a
44 comparison of radiation levels impinging ahead of flame fronts, with heights in the range of
45 0.3–6 m, exhibited significant differences. Therefore, real-scale fire experiments that are
46 representative of most of the physical processes involved in wildfires are needed to gain a
47 deeper understanding of how they spread and to establish useful safety distances for fire
48 managers. To this end, measuring devices dedicated to wildfire applications must be
49 developed, since instrumentation in the field has raised logistical problems that need to be
50 overcome.

51 Some experimental fires were conducted on a large scale (Cheney *et al.* 1993, Cheney and
52 Gould 1995, Fernandes 2001, Carrega 2002, Viegas *et al.* 2002, Bilgili and Saglam 2003, De

53 Luis *et al.* 2004, Vega *et al.* 2006). However, these studies only provided observations or
54 measurements of the macroscopic characteristics of the flame front (rate of spread, flame
55 length, flame tilt angle, residence time, etc.). Temperature and heat fluxes were measured less
56 frequently (Packam and Pompe 1971, Gould *et al.* 1997, Butler 2003, Stocks *et al.* 2004,
57 Butler *et al.* 2004, Cohen 2004, Silvani *et al.* 2005, Santoni *et al.* 2006, Morandini *et al.* 2006,
58 Silvani and Morandini 2009). The data available in the related literature are summarised in
59 Table 1.

60 Such measurements, obtained on a large scale, are also needed to improve and validate
61 physical-based modelling of wildfires (Morvan and Dupuy 2004, Linn and Cunningham
62 2005, Porterie *et al.* 2005a, Mell *et al.* 2007). Caution should be exercised when predicting
63 fire spread with models or sub-models developed from and/or validated against laboratory
64 experiments, since these formulations can be misleading when applied to large-scale fire
65 scenarios. For instance, if thermal degradation of the vegetative fuel is modelled by laws
66 established for low heating rates or low masses of the samples, i.e. conditions which are not
67 representative of the mechanisms involved in wildfire spread, extrapolation to a larger scale is
68 prone to errors. Measurements obtained from large-scale experiments are also expected to
69 provide some guidance or validate predictions of fire safety zones (Butler and Cohen 1998,
70 Dupuy and Morvan 2005, Kaiss *et al.* 2007) and wildland urban interface dimensioning
71 (Cohen 2004, Consalvi *et al.* 2005, Porterie *et al.* 2005b). Some of these modelling
72 approaches (Butler and Cohen 1998, Cohen 2004, Kaiss *et al.* 2007, Zarate *et al.* 2008) are
73 based on purely radiative models in which the role of convection is neglected—an approach
74 that may not be correct. Indeed, previously proposed physics-based models of fire spread
75 under wind-blown conditions (Pagni and Peterson 1973, Porterie *et al.* 2000, Morvan and
76 Dupuy 2004, Mell *et al.* 2007, Morvan *et al.* 2009) predicted the existence of a significant
77 convective flux on top of the fuel layer in some configurations.

78 Fire spread results from the interaction of many processes: heat and mass transfer, thermal
79 degradation of the combustible material and reactions in gaseous and solid phases.
80 Understanding the heat transfer mechanisms governing fire propagation across vegetative
81 fuels is thus of great interest in fire research and forest management. Fire grows and spreads
82 across vegetative fuels by direct burning, which results from impingement of the flame on
83 combustible materials, and from heat transfer towards the unburned fuel by means of
84 radiation and/or convection (combustion products). Environmental factors such as wind,
85 topography and vegetation type can affect the rate and direction of heat transfer and resulting
86 fire spread. These parameters can be controlled in small-scale experiments in the laboratory.
87 However, the slope, fuel and particularly wind are hardly controllable when conducting fire
88 experiments in the field, i.e. under conditions close to those encountered in wildfires. The
89 variability of these conditions in the open explains the drastic changes in fire dynamics which
90 are responsible for many firefighter casualties during interventions. The most significant
91 effects are observed in the flame front properties and dynamics. The volume of reacting gases,
92 amount of heat release and the span of incident radiation can increase by several orders of
93 magnitude during fire spread; even for a given set of ambient conditions, the fire front can
94 propagate within a wide range of spread rates (Viegas 2006). This is the main reason why it is
95 difficult to extrapolate fire spread mechanisms from the laboratory to the field. Data
96 collection in the field is thus the best alternative for understanding the fire spread processes
97 and for validating or improving models. These considerations are the main motivation for
98 developing new measurement devices capable of collecting data in the field during fire
99 spread.

100

101

102 **Materials and methods**

103 *Fire experiments procedure*

104 Five experimental fires were conducted in the Mediterranean region (south of France) across
105 plots of shrublands. The fires were lit along the windward edge of the plots using a petrol
106 torch. The lengths of the ignition lines were 20–30 m to replicate wildfire conditions. The
107 orientation of the plot was chosen according to the main prevailing wind direction to ensure
108 wind-aided fire spread conditions. A detailed description of the plot characteristics and
109 environmental conditions are provided in Table 2. The experiments were conducted under
110 various vegetation properties, wind conditions and plot topography, but the focus of this study
111 was on characterising the heat transfer ahead of the flame front.

112

113 *Plots and fuel properties*

114 Plots with vegetative fuel as homogeneous as possible and high vegetation cover (coverage >
115 95%) were chosen for the fire experiments. The basic properties of the vegetation were
116 measured and are provided in Table 2. The dominant species were *Syrmatium glabrum*,
117 *Arbutus unedo*, *Genista lobelia*, *Erica arborea* and *Asphodelus albus*. Before the fire
118 experiments, the total fuel load (dead and live fuel from litter and canopy) and vegetation
119 height were measured from three sample areas of 1 m² in size. Samples were taken close to
120 the experimental plots so that the vegetation cover would not be modified. Fuel moisture
121 content was obtained from three samples of the most abundant species. Samples were oven-
122 dried at 60°C for 24 h, and the fuel moisture was expressed as a percentage of the dried
123 weight (Allgöwer *et al.* 2006). The amount of fuel removed by the fire, i.e. the fuel
124 consumption, was expressed as the ratio of the amount of char remaining after the fire, over
125 the three 1 m² sample areas, to the fuel load.

126

127 *Measurement devices*

128 The heat flux and gas temperature during the fire spread experiments were measured by an
129 intrusive sensor system capable of resisting the fire (Silvani and Morandini 2009). The device
130 consists of two heat flux gauges and a thermocouple fixed to a steel support facing the
131 approaching fire front. It is designed to be fast and easy to set up (less than 30 min) with the
132 possibility to be deployed in forest fires. The inside of the device was coated with a 4-cm
133 thick layer of insulating material (ceramic felt); the inside temperature never exceeded 70°C
134 during the experiments. In every case, the measurements were made close to the top of the
135 vegetation using different supporting rods. A photograph of this device is shown in Fig. 1.

136 The gas temperature was measured using a K-type thermocouple with a 250- μm -diameter
137 grounded junction. This configuration was chosen to guarantee a good compromise between
138 accuracy and resistance; fine wire thermocouples are less affected by radiation effects and
139 have a faster response (Cox and Chitty 1985), which allows the rapid fluctuations of the gas
140 temperature to be recorded with good accuracy. The response time of the thermocouples used
141 in this study was less than 0.2 s. Each thermocouple was covered with a ceramic insulator and
142 inserted in a 10-cm-long stainless steel tube, leaving the junction to protrude from the device.
143 These devices provided information on the flame residence time and peak temperature.

144 The total and radiant heat fluxes emitted from the flame front during the fire spread were
145 measured with Medtherm transducers (16H and 64 Series). A sapphire window attachment
146 was added to the radiant heat flux transducer to eliminate the convective heat being
147 transferred to the sensing area. These transducers were calibrated by the manufacturer to 0–
148 200 kW m^{-2} and had a response time of less than 0.25 s, which provided accurate
149 measurements for an approaching fire front. The transducers were oriented towards the flame
150 front and had a view angle of 150°. A thermocouple recorded the body temperature of the
151 gauge.

152 Thermocouples and heat flux gauges were plugged into a power-supplied data logger
153 buried 0.3 m under the ground surface to protect it from the fire. Extension cables insulated
154 by a Teflon coating, a layer of ceramic and an outer layer of aluminium connected the sensors
155 to the underground data logger by passing through the steel tube of the support carrying the
156 sensors. This configuration was chosen to allow the use of short extension cables (1.5 m) to
157 reduce the measurement errors. The transducers signals were recorded at a sampling rate of 1
158 Hz. This sampling frequency matched the response time of the sensors used.

159 The wind, which can be highly variable in the open, is one of the most significant variables
160 influencing fire spread (Cheney *et al.* 1993). The wind velocity and direction were recorded
161 using a two-dimensional ultrasonic anemometer 2.5 m above the ground surface to reflect the
162 average wind acting on the fire front. The anemometer was located on the downwind edge of
163 the vegetation plot to minimise the influence of the fire on the wind measurements.
164 Furthermore, such a location protected the ultrasonic transducers from smoke and large-
165 diameter firebrands generated by the fire which can affect sonic measurements. The wind data
166 were recorded using another (synchronised) data logger at a sampling rate of 1 Hz.

167 Finally, to obtain accurate observations of the fire spread, three digital video cameras were
168 used to record the rear, front and side views of the fire. The video recordings (25 images per
169 second) provided information on the rate of fire spread and the geometric properties of the
170 flame, i.e. the flame height and tilt angle. A virtual grid was drawn on the video images by
171 means of reference marks placed regularly every 5 m. The known positions of these marks
172 helped to relate the position and dimensions of the flame on the virtual grid to its real position
173 and dimensions on the field. The rate of spread was obtained from the slope of the curve
174 representing the fire front position versus time. About eight data points were obtained for
175 each curve by timing the arrival of the fire front head to the reference marks. A least squares
176 regression was used to fit a straight line to these points. The flame front depth was computed

177 from the product of the residence time and the rate of spread. The flame length and height
178 were defined along the mean flame axis and the vertical, respectively. The flame tilt angle
179 was defined as the angle between the terrain and the leading surface of the flame.

180

181

182 **Results and discussion**

183 *Fire front properties and behaviour*

184 Every experimental plot was ignited as a line fire along the windward plot edge; the fire fronts
185 developed a curvilinear shape during their spread. Details of the environmental conditions and
186 related fire properties are reported in Table 2. The average wind properties remained nearly
187 constant during the experiments, and the fires reached a quasi-steady state. The steady
188 correlation factors (R^2) for the least squares regression, which was computed to obtain the rate
189 of spread, were in the range of 0.86–0.96. These high R^2 values are a good indicator of fire
190 steadiness. The vegetative fuels were mostly composed of fine materials (needles, leaves and
191 twigs) with diameters that were lower than 2 cm; consequently, the fuel consumption was
192 very high for the set of experiments. The fireline intensity, which represents the heat released
193 per unit time per unit length of the fire front, is defined as the product of the weight of fuel
194 consumed (kg m^{-2}), the heat yield of the fuel (assumed to be 18 000 kJ kg^{-1} for most
195 vegetative fuel) and the rate of spread (m s^{-1}). The measured fire intensities were in the range
196 of 8 300–31 000 kW m^{-1} . These values are consistent with the intensities measured during the
197 experiments across similar fuel loads (Table 1). The high intensities measured during
198 experiments 1–3 (16 000–31 000 kW m^{-1}) can be attributed to the significant fuel load (4.1–
199 7.4 kg m^{-2}) of particular vegetal species (*Syrmatium glabrum* and *Genista lobelia*). Fire tests
200 conducted across these broom species, which are very inflammable, generate high intensities
201 with fire fronts travelling very fast even under low-risk conditions (wind velocity $< 5 \text{ m s}^{-1}$,

202 high fuel moisture content). It should be noted that post-fire measurements were performed at
203 least 1 h after the passage of the fire front, when the temperature had decreased to a sufficient
204 extent to allow the safe sampling of the remaining char. During this time period, mass loss
205 continued due to char oxidation from large-diameter materials (>2 cm) which did not
206 participate in the spreading of the pyrolysis front; thus, the amount of fuel actually consumed
207 within the flaming front was overestimated. Furthermore, the rate of spread was determined at
208 the fire head or at the most advanced point of the fire front; this was because the initial
209 straight line of ignition was observed to change to a parabolic shape when quasi-steady
210 propagation was achieved. Both sources of errors contributed to overestimation of the fireline
211 intensity.

212 Qualitative observations of the fire spread from video recordings revealed the
213 existence of two types of fires according to the flame front properties and behaviour.
214 Photographs of the fire spread in experiments 2 and 4 are shown in Fig. 2. In the first type of
215 fire (experiments 1, 2 and 3), the flames stood up (flame heights were about 5 m) and the
216 smoke plume was guided upwards to produce a nearly vertical convection column. The flow
217 strongly responded to the heating and buoyancy forces generated by the fire (Fig. 2a), and no
218 smoke was observed to flow ahead of the fire front. In the second type (experiments 4 and 5),
219 the inertial forces exceeded the buoyancy forces, and the flow did not respond to heating
220 generated by the fire. In this case, the buoyancy forces generated by the fire were weaker
221 because of the lower fuel load. The flame front was greatly tilted forward (Fig. 2b), and the
222 flame height was about 1.5 m. The top of the unburned vegetation layer was subjected to
223 intermittent lapping by the flames, and the fire travelled quickly across the vegetation. The
224 smoke flowed close to the top of the vegetation, embedding the unburned vegetation within a
225 layer of hot gases released by combustion. In the following sections, the effects of the fire
226 behaviour on the temperature and heat flux measurements are examined.

227

228 *Gas temperature*

229 Thermocouples are commonly used in fire research to measure gas temperatures, but they
230 often fail to measure the true gas temperature (Cox and Chitty 1985, Luo 1997, Dupuy *et al.*
231 2003, Silvani and Morandini 2009). Radiation effects that depend on the measurement
232 conditions are the most significant sources of errors. Discrepancies between the true and
233 measured gas temperatures are considered acceptable since the error range of the probes used
234 in this study is less than 10% (Silvani and Morandini 2009). The corrected temperature curves
235 are not provided here, but the effects of radiation on the thermocouple measurements must be
236 kept in mind.

237 The flame residence time for each experiment is listed in Table 2 and is defined as the time
238 during which the temperature is greater than 500°C, which corresponds to the visible flame
239 temperature (Drysdale 1985). The flame residence times did not show significant differences
240 and thus could not account for the two fire spread behaviours identified previously.

241 The temperature-time curves for the five experiments are shown in Fig. 3. The air
242 temperature measured during the fire spread showed the presence of three regions: preheating,
243 flaming and charring. These regions are delineated by two vertical dashed lines in Fig. 3,
244 using the previously defined flame temperature criteria. The measured temperatures began at
245 the ambient temperature and increased to a maximum of about 800–900°C, which is the usual
246 temperature range for burning vegetal fuels. The temperature curves show a slow trend
247 modulated by fast fluctuations. The slow trend, or the low-frequency part of the signal, is
248 related to the fire spreading, while the fluctuations are due to flame pulsations and wind gusts
249 (Morandini *et al.* 2006).

250 In the first group of experiments, the air temperature remained close to the ambient value
251 before the arrival of the fire front. The rate of the rise in air temperature from ambient to

252 ignition was computed from low-pass filtered signals (Silvani *et al.* 2005) and is provided in
253 Table 2. The corresponding flame fronts (Fig. 2a) were close to the vertical, and the smoke
254 plume was guided upward. Some peculiarities in the temperature behaviour were observed in
255 experiment 2. The temperature suddenly dropped to 200°C for about 20 s due to the presence
256 of discontinuities in the fuel; these resulted from animal paths that passed through the
257 experimental plot. These discontinuities induced local extinction of the fire. The
258 measurements made in the preheating region, which are of greater interest, were not
259 influenced by this vegetation discontinuity. The rising temperature rate during preheating in
260 the second group of experiments was about one-fifth lower than that in the first group.
261 Furthermore, the increase in air temperature occurred over a longer period before flame
262 contact (more than 100 s prior to the ignition of vegetation), and the temperature
263 measurements showed high fluctuations. These fluctuations were higher in the second group
264 than in the first because of the presence of the smoke plume as well as the intermittent lapping
265 at the top of the vegetation by the flame (Fig. 2b).

266 Computing the correlation coefficient and related confidence intervals helps to determine if
267 a statistical relation exists between temperature and wind velocity fluctuations. The
268 correlation coefficient between temperature and velocity is given by:

$$269 \quad r = \frac{\text{cov}(T, u)}{\sigma_T \sigma_u} \quad (1)$$

270 where *cov* is the covariance of temperature *T* and longitudinal wind velocity *u*, and σ is the
271 standard deviation. The square of *r*, namely, the coefficient of determination r^2 , is used to
272 measure the association between both variables. The coefficient of determination is the
273 fraction of the variance in *u* that is accounted for by changes in *T* and the linear relationship
274 between *u* and *T*. A confidence level of 95% and sample size of 100 s were chosen. As
275 expected, the correlation between temperature and wind velocity was better in the second

276 group of experiments ($r^2 = 0.2$) than in the first group ($r^2 = 0.015$). In addition, a confidence
277 level of 80% and sample size of 200 s were also tested. In the first group of experiments, the
278 confidence interval width remained at around 0.01. In contrast, the confidence interval width
279 increased to around 0.2 when either the confidence level increased or the sample size
280 decreased. The r^2 statistical convergence can thus be enhanced by increasing the sampling
281 rate. The r^2 value showed a considerable decrease when r decreased by one-tenths of its
282 original value. Indeed, the r^2 values in the range of 0.2–0.3 coincided with r values in the
283 range of 0.5–0.6. In contrast, r was about 0.1 when r^2 was lower than 0.05. Although the
284 correlation between T and u is not linear, a statistical relation cannot be ignored in the second
285 group of experiments, while it can be neglected for the first group. In other words, wind did
286 not significantly influence heat transfer ahead of the flame front in the first group of
287 experiments. Conversely, in the second group of experiments, coupling between wind and
288 temperature was observed in the preheating region. Indeed, the correlation coefficient
289 between temperature and velocity as well as the fluctuating nature of the temperature signal
290 suggest the presence of convective heat transfer in the preheating region. In this case, the
291 unburned vegetation was embedded into a wind-driven smoke layer (Fig. 2). However, to
292 obtain a correct representation of the heat transfer processes governing fire spread, it was
293 necessary to simultaneously use several sensors scattered through the vegetation plot during
294 the experiments. The mechanisms governing heat transfer towards unburned vegetation may
295 be different at the fire head or flanks. Numerical simulations in the presence of an ambient
296 wind (Mell *et al.* 2007) showed that the flanks of the fire perimeter spread under conditions
297 alternating between heading and baking fires, which influences the heat transfer processes. In
298 general, because the information collected by a thermocouple is local in nature, it is not
299 adequate to investigate the heat transport phenomena using single-point measurements, and

300 measurements of temperature distributions or integral quantities such as heat fluxes should be
301 preferred.

302

303 *Heat fluxes*

304 The time evolution of the total and radiant heat fluxes measured during the fire spread
305 experiments are shown in Fig. 4. The preheating, flaming and charring regions can also be
306 observed in these curves. The heat fluxes progressively increased up to maximum values
307 exceeding 100 kW m^{-2} when the flame was in contact with the measurement device.
308 However, caution should be exercised in interpreting the heat flux measurements in a mixed
309 radiant-convective environment, especially those obtained from total heat flux gauges. The
310 calibration process consists of determining the sensitivity ($\text{kW m}^{-2} \text{ mV}^{-1}$) of the transducers in
311 comparison to the output voltage of a known calibration source. The calibration should ideally
312 be performed in a thermal environment similar to the one in which the gauges will be used;
313 however, gauge calibration is usually performed using radiant sources such as a black body,
314 furnace or radiant panel. It may not be entirely appropriate to measure the total heat flux using
315 a Gardon gauge through radiation-based calibration in a mixed radiative-convective
316 environment such as a fire (Bryant *et al.* 2003). The gauge sensitivity differs for radiative and
317 convective contributions; a method to estimate measurement uncertainties from total gauges
318 in a mixed radiative-convective environment has been proposed (Kuo and Kulkarni 1991).
319 This method allows the total incident flux to be calculated when calibration is based only on
320 radiative flux. Bryant *et al.* (2003) highlighted the uncertainties caused by convection when
321 radiation is the quantity under consideration and proposed a method to calculate the incident
322 radiant heat flux from total gauges. In both cases, the applied corrections are obtained from
323 the thermal diffusion equation for a foil and are expressed according to the convective heat
324 transfer coefficient or the Nusselt number, which depends on the thermophysical properties of

325 the fluid (density, specific heat at constant pressure, viscosity and thermal conductivity) in
326 contact with the gauge, the velocity of the fluid, the flow regime (turbulent or laminar), the
327 nature of convection (natural or forced convection) and the geometry of the surface of the
328 heated gauge. The uncertainties in determining the parameters of the correction method, i.e.
329 the convective heat transfer coefficient or the Nusselt number, make these corrections difficult
330 to apply. A previous work (Silvani and Morandini 2009), quantified the error when following
331 the method proposed by Kuo and Kulkarni (1991); it was determined that the total heat flux is
332 underestimated in the flaming region.

333 The radiation heat flux transducers are not subject to such uncertainties since the window
334 attachment eliminates convection. Nevertheless, these gauges may suffer from deposition of
335 soot on the sapphire window attachment. The use of gas purging eliminates soot deposition,
336 but this is not easy to implement in the field. To clarify the deposition of soot on the
337 radiometer window, a preliminary study was conducted in the laboratory using fires from a
338 forest fuel burner (Appendix 1). The results showed that the deposition of soot on the gauge
339 window can be considered negligible when the radiometer is only exposed to smoke, but
340 flame contact with the gauge leads to the deposition of a significant quantity of soot on the
341 window. For this reason, the radiation heat flux gauges underestimate radiation inside sooty
342 flames; thus, only the measurements ahead of the fire front are considered in the following
343 sections.

344 Using two different gauge types allows the qualitative partitioning of the convective and
345 radiative processes in the preheating region. When the total and radiation heat fluxes coincide,
346 heat transfer ahead of the fire front is dominated by radiation, and gauges provide accurate
347 quantitative measurements. Conversely, greater discrepancies between the two signals
348 indicate preheating due to mixed radiant-convective heat transfer. By integrating the heat flux
349 curves ahead of the flame front, the differences between radiation and total heat fluxes can be

350 evaluated in the preheating region. In the first group of experiments, these differences were
351 lower than 10%, so radiation could be considered as the dominant heat transfer process ahead
352 of the fire front. In the second group of experiments, the measurements revealed the non-
353 negligible contribution of convective preheating for the unburned fuel, but the heat flux levels
354 were lower. The difference between the radiation and total heat fluxes was as great as 50%
355 (experiment 4). These results confirm the existence of a convective component ahead of the
356 flame front. The significant role of convective heat transport in the overall thermal balance
357 ahead of the flame front is related to the stronger correlation between fluctuating temperature
358 and wind velocity fields. This study did not focus on the quantitative measurement of the
359 convective exchange between the hot gas stream and vegetation. Aside from the previously
360 mentioned problems of radiation-based calibration for total heat flux gauges in a mixed
361 environment, the convective heat transfer coefficient of the transducer was different from that
362 of the fuel particles. The geometric properties (shape and orientation) and thermal
363 conductivity of the fuel particles should be taken into account to estimate convective heating
364 from the viewpoint of the vegetation. Furthermore, the vertical velocity profile within the
365 vegetation has significant effects on advection, and convective heating varies within the fuel
366 layer. For instance, quantitative measurements of the convection above the vegetation can be
367 performed by determining the temperature and velocity fields using thermocouples and
368 particle image velocimetry, respectively.

369

370 *Heat transfer mechanisms governing fire spread*

371 The different heat transfer processes ahead of the fire front that are observed between the two
372 groups of experiments are influenced by changes in the fire plume properties and affect the
373 time needed for the unburned vegetation to ignite. The time during which the unburned
374 vegetation is exposed to a radiation heat flux greater than 13 kW m^{-2} is provided in Table 2

375 for the set of experiments. This threshold value corresponds to the minimum radiation heat
376 flux needed to ignite volatile matter from the vegetative fuels by a pilot flame (Drysdale,
377 1985). The exposure time to radiation was significantly longer in the first group of
378 experiments than in the second group. These results show that in the first group of
379 experiments, the preheating mechanisms ahead of the fire front were governed by radiation.

380 The longitudinal variation in the radiation heat flux impinging upon the unburned
381 vegetation is shown in Fig. 5. The data were deduced from flux-time measurements
382 considering a steady rate of fire spread. The flux-time signals were first filtered before time-
383 to-space transformation with a Butterworth filter to eliminate high signal frequencies (Silvani
384 *et al.* 2005). This process allowed a better representation of the mean spatial distribution for
385 radiation impinging ahead of the fire front. The distance to the fire front was estimated by
386 multiplying the time to ignition by the rate of spread for each experiment. The spatial
387 distribution of the heat fluxes ahead of the flame front confirmed the existence of two fire
388 spread processes. In the first group of experiments, radiation ahead of the flame front
389 presented some characteristic length scales or impact distances (lengths across which
390 radiation level was greater than the threshold of 13 kW m^{-2}) of about three times the flame
391 height. Thermal radiation is a long-range process and is usually considered as the dominant
392 mode of heat transfer, which determines the growth and spread of large-scale fires (Sacadura
393 2005). Incident radiation plays a significant role in the thermal degradation of the fuel through
394 processes such as water evaporation and fuel pyrolysis. Heat flux measurements were
395 performed above the vegetation; therefore, they are related to the energy impinging on the top
396 of the fuel layer, i.e. the incident radiation. The typical absorptivity of vegetation in the
397 Mediterranean region, which depends on fuel properties (spectral, shape, orientation and
398 moisture content), is around 0.9 with reference to the radiation emitted by a black body at
399 1000°C (Monod *et al.* 2009). The top of the vegetation absorbed most of the thermal radiation

400 measured by the transducers. The radiation mean path length within the vegetation was
401 smaller, as was the radiation penetrating inside the fuel layer.

402 For experiments 1–3, the measurements showed significant radiation levels up to 10 m
403 from the fire front (Fig. 5). The thermal degradation of the vegetative fuel due to radiant
404 heating began several meters ahead of the flame front. It is argued that the fire spreading
405 scenario, which involves ignition of the mixture formed by these combustible gases and by
406 the oxidiser located ahead of the flame front, is most commonly observed in wildland fires.
407 Most safety criteria (fuel breaks or wildland-urban interfaces) are based on a radiation-
408 dominated fire spread (Butler and Cohen 1998, Cohen 2004, Zarate *et al.* 2008). However, the
409 present heat flux measurements indicate the existence of a different scenario. In the second
410 group of experiments, the radiation level ahead of the flame front was lower than 13 kW m^{-2}
411 (Fig. 5); this value is too low for sustained pyrolysis of the vegetative fuel to occur. In this
412 case, the fire spread by convection heating, which is related to the intermittent licking of the
413 top of the unburned vegetation by the flame. Physics-based models developed in previous
414 studies (Morvan and Dupuy 2004, Linn and Cunningham 2005, Morvan *et al.* 2009) predicted
415 a change in the fire spread regime dominated by either radiation or convection under low or
416 high wind conditions, respectively. This change in the fire spread regime is usually predicted
417 using the convective Froude number F_c (Clark *et al.* 1996) or the convection number N_c
418 (Nelson 1993). These dimensionless numbers represent the ratio of the inertial forces induced
419 by wind flow and the buoyancy forces generated by combustion. The convective Froude
420 number and convection number are given by:

421
$$F_c = \sqrt{\frac{(u - r)^2}{g \frac{\Delta \theta}{\theta_a} \ell}} \quad (2)$$

422
$$N_c = \frac{2 g I}{\rho C_p \theta_a (u - r)^3} \quad (3)$$

423 where u stands for the average wind velocity (m s^{-1}), r is the rate of fire spread (m s^{-1}), g is the
424 acceleration due to gravity (m s^{-2}), $\Delta\theta$ is the difference between the temperatures of the hot
425 gases and the surroundings, θ_a is the temperature of the surroundings (K), I is the fireline
426 intensity (kW m^{-1}), ρ is the air density (1.2 kg m^{-3}) and C_p is the specific heat of dry air at
427 constant pressure ($1.005 \text{ kJ kg}^{-1} \text{ K}^{-1}$). The variable ℓ (m) is a characteristic length scale of the
428 flame front which is representative of buoyancy forces generated by the fire, i.e. the flame's
429 length, L , depth, D or height, H .

430 In numerical simulations (Pagni and Peterson 1973, Clark *et al.* 1996, Morvan and
431 Dupuy 2004, Morvan 2006), researchers suggested that $F_c^2 < 1$ (resp. $N_c > 1$) indicates a
432 plume-dominated fire, while $F_c^2 > 1$ (resp. $N_c < 1$) indicates a wind-driven fire. In this study,
433 the convective Froude and convection numbers (Table 2) were lower than 0.4 and greater than
434 14, respectively. These results therefore confirm the conclusions of Sullivan's analysis of
435 grassland fires (Sullivan 2007). Neither dimensionless number reflects the observed
436 behaviour of wind-driven fires at the field scale and both numbers seem more appropriate for
437 quantifying academic fire spread scenarios such as laboratory-scale experiments or numerical
438 simulations. The wind-driven fire spread regime, in which the contribution of convection
439 becomes significant due to contact of the fire plume with unburned vegetation, should be
440 taken into account when managing safety zones. Simulation results (Porterie *et al.* 2005b,
441 Morvan 2006) also pointed out that convection cannot be neglected in predicting fire safety
442 zones when plume impingement occurs. Morvan and Dupuy (2004) clarified that for wind-
443 driven fires, radiation and convective heat transfer initially have the same order of magnitude;
444 however, fire propagation is subsequently controlled by convective heat transfer, which can
445 represent up to 70% of the energy received by the solid fuel. The existence of such a regime,
446 which is favoured by a low fuel load (generating less buoyancy forces) on steep slopes and
447 under wind-aided conditions, suggests that the dimensioning of fuel breaks in vegetal cover

448 may not be appropriate if it is based only on a purely radiative evaluation of the impact
449 distance.

450

451

452 **Conclusion**

453 The heat transfer mechanisms ahead of a flame front were investigated in the field to further
454 our understanding of how wildfires spread. Within the range of experimental configurations
455 considered (wind velocities $< 5 \text{ m s}^{-1}$), the collected data indicated the existence of two fire
456 spread regimes. The first regime, which occurs for higher fuel loads, is plume-dominated. In
457 this case, the flow strongly responds to the great buoyancy forces generated by the fire:
458 flames and smoke plume are guided upward. Radiation is the dominant heat transfer
459 mechanism ahead of the fire front. The second regime, which occurs for lower fuel loads, is
460 wind-driven. In this case, the flow is governed by inertial forces due to wind: flames and
461 smokes travel close to the top of the vegetation. Preheating of the unburned fuel occurs due to
462 mixed radiant-convective heat transfer. The flame front spreads quickly by direct contact with
463 unburned fuel. Within the range of experimental conditions considered in this study, it was
464 found that the Clark's convective Froude number and Nelson's convection number, which are
465 used in numerical studies to predict the fire spread regime, did not reflect the observed
466 behaviour of the wind-driven fires in the field. The complexity of the turbulent wind flow
467 modified by the fire needs further investigation to assess the role of convective heat transfer
468 in greater detail. Convection can endanger fuel break efficiency or firefighter safety if these
469 distances are determined according to radiation only.

470

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478

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605

606

607 **Appendix 1**

608 A preliminary study of the deposition of soot on the radiometer window was conducted in the
609 laboratory using two radiation heat flux transducers with sapphire windows and fires from a
610 forest fuel burner. The burner was made from a 50-cm-diameter basket filled with 500 g of
611 forest fuel (*Pinus pinaster* needles) and ignited using alcohol. Prior to each fire test, both
612 radiometers were exposed to a radiant source of about 60 kW/m² in order to check the good
613 agreement (Table A). In the first test, one radiometer was exposed to a smoke plume about 50
614 cm above the flame for 200 s. After exposure, the measurements of the heat flux gauge
615 exposed to smoke were compared to those of the soot-free reference radiometer. In the second
616 test, the radiometer was exposed to the flame for 60 s, and the measurements obtained were
617 compared with those of the reference radiometer. The attenuation of the gauge reading after
618 smoke exposure was not significant. These results confirm that the deposition of soot on the
619 gauge window can be considered as negligible when the transducer is only exposed to smoke

620 (in the preheating region, for instance). This is due to the well-ventilated nature of the flame
621 in the open in contrast with fire in an enclosure. In contrast, flame contact with the gauge
622 deposited a significant quantity of soot on the window. In this case, the attenuation measured
623 during this test was about 25%; therefore, radiation measurement in the flaming region could
624 no longer be considered. When the radiometer is used in a hostile flame environment,
625 nitrogen purging is used to prevent soot deposition in order to keep the radiation transmitting
626 window clean. The purge system requires the use of an inert gas which flows ahead of the
627 window to prevent soot from depositing on it. Another alternative is the use of ellipsoidal
628 radiometers with gas purging to prevent soot from entering its cavity.