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Supplementary Material

On the intermittent nature of forest fire spread – Part 2

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Supplementary Appendix S1

Laboratory Experiments

Laboratory experiments were carried out at the Forest Fire Research Laboratory of the University of Coimbra using indoor test Tables. The fuel used in all tests was composed of dead needles of *Pinus pinaster* with a fuel load M_c of 0.6 kg m^{-2}(dry basis). In all tests the ROS R_o of a linear fire on a horizontal fuel bed was evaluated and the respective values are given in the Tables S1, S2 and S3.

The canyon tests (DE) were performed in the Canyon Table MD 2 that has two faces of 3 × 3 m^2 that can be modified to take the shape of a canyon as described in Viegas and Pita 2004, Viegas 2004.

The junction fires (JF) and the slope tests were performed on Combustion Table DE4 which has a useful surface of 6 × 8m^2 and can be inclined up to 40º. In the JF a triangular shaped fuel bed 5.0m long was placed at slope angles between 0º and 40º. The two sides of the triangle making 30º were ignited simultaneously and the spread of the head fire was analysed using the methodology described in Raposo *et al.* 2018.

The slope tests were performed using a fuel bed of 2 × 5.5 m^2 with a point ignition 0.5m above its edge. The ROS of the head fire was tracked using the same methodology as Viegas *et al.* 2021.

Table S1. Parameters of canyon tests

Ref.	δ (º)	α (º)	*Test*	m_f (%)	R_o (cm s^{-1})
1	40º	20º	DEP201	10.98	0.29
2			DEP202	11.98	0.29
3			DEP203	10.50	0.29
4			DEP204	10.30	0.28
5			DEP205	10.30	0.29
6		30º	DEP301	10.30	0.28
7			DEP302	8.51	0.28
8			DEP303	13.01	0.28
9			DEP304	10.70	0.27
10			DEP305	10.30	0.29
11		40º	DEP401	7.60	0.30
12			DEP402	8.10	0.28
13			DEP403	9.00	0.28
14			DEP404	13.00	0.21
15			DEP405	10.70	0.27

Table S2. Parameters of slope tests

Ref.	α (º)	**Test**	**Test** dimensions (m^2)	m_f (%)	R_o ($cm\ s^{-1}$)
1	20	SP201	5 × 2	12.5	0.31
2		SP202	5 × 2	13.8	0.26
3		SP203	5.5 × 2	17.9	0.21
4		SP204	5.5 × 2	17.1	0.21
5	30	SP301	5 × 2	12.5	0.31
6		SP302	5 × 2	13.8	0.26
7		SP303	5.5 × 2	17.0	0.21
8		SP304	5.5 × 2	18.2	0.21
9	40	SP401	5 × 2	12.5	0.31
10		SP402	5 × 2	13.8	0.26
11		SP403	5.5 × 2	16.4	0.21
12		SP404	5.5 × 2	17.1	0.21

Table S3. Parameters of Junction Fire Tests

Ref.	θ (º)	α (º)	**Test**	**Fuel**	m_f (%)	R_o ($cm\ s^{-1}$)
1	30	0	CF43	PP	17.37	0.15
2	30	20	CF44	PP	20.91	0.17
3	30	30	CF45	PP	19.05	0.17
4	45	30	CF47	PP	19.48	0.18
5	30	20	CF53	PP	15.61	0.24
6	30	30	CF54	PP	15.74	0.22
7	30	30	CF55	PP	15.74	0.22
8	30	0	CF61	PP		

Supplementary Appendix S2

Gestosa Field Experiments

The field experimental fires were performed in the Lousã Mountain range, central Portugal, in three sets of experiments. This area, the *Gestosa* test field, provides similar conditions of fuel and topography, in a region characterized by having warm temperate climate with dry summer, following the Köppen–Geiger climate classification (Kottek *et al.* 2006).

In the plots used the minimum altitude is 702m (ASL), in plot 13_04, and the maximum is 1100m (ASL), in plot 804. The majority of the plots have a Southwest orientation (between 209 and 256º north), one is facing west (plot 808), another facing northwest (plot 809) and three of them face northeast (2011 tests).

According to the Lithologic Chart of Portugal (Silva 1983), the prevailing soils are derived from a *Schist-grauvaquic* complex. They are classified as *Humic Cambisols*, formed from materials resulting from alteration and disaggregation of the underlying rock substratum (consolidated rocks).

The typical vegetation of the area is composed of a continuous homogeneous mixture of shrubs and in some areas isolated maritime pine trees (*Pinus pinaster*). The dominant shrub species found are *Erica umbellata*, *Erica australis*, *Chamaespartium tridentatum*, *Ulex sp*. and *Halimium ocymoides*.

The plots layout was defined each year according to the specific objectives of the tests. Fire breaks were opened either manually, with hand tools, or in some cases when the vegetation was higher, mechanically. Prescribed burning techniques were also used to create larger safety zones. The width of the fire breaks varied between 5 and 20 m according to their location. In 2002 and 2006 the plots were rectangular, but in 2011 triangular plots were tested. In Raposo *et al.* (2018), tests 13_01, 13_02 and 13_04 are referred to respectively as CF57, CF78 and CF79.

Drip torches were used to produce linear ignitions at the bottom of the plots in 2000 and 2006. In 2011, in order to have a simultaneous ignition on both laterals of the triangular plots, pyrotechnic ignition was used.

Fire progression was determined after processing the images captured using infrared cameras.

Table S4 presents the main characteristics of the plots referred here.

Table S4. Summary of the main characteristics of the test plots

Ref	Year	Plot	Dimensions (W × L) (m)		Slope (º)	Orientation (Degrees from north)	Fuel height (m)	Fuel Load (Kg m^{-2})	Ignition
1	2000	40	90	155	13.9	219	0.75	1.925	Linear
2		41	95	140	19.0	238	0.69	2.356	Linear
3		42	90	160	16.7	220	0.55	1.556	Linear
4		43	110	150	21.7	232	0.87	2.062	Linear
5		44	90	130	27.1	219	1.06	2.631	Linear
6		45	90	130	24.0	209	0.64	1.904	Linear
7	2006	804	40	56	10.4	215	0.43	2.610	Linear
8		807	43	56	16.4	256	0.39	2.500	Linear
9		808	35	40	17.8	270	0.42	2.760	Linear
10		809	28	40	18.0	299	0.52	4.140	Linear
11	2011	13_01	27[A]	46	17.5	48	0.77	3.792	Linear (2 Laterals)
12		13_04	27[A]	45	20.7	45	0.73	3.855	Linear (2 Laterals)
13		13_02	42[A]	94	18.6	40	1.23	4.344	Linear (2 Laterals)

[A]V-shaped plots. The width refers to the top of the plot

Supplementary Appendix S3

Large Fires

Case 1 - Sundance Fire

The Sundance fire is described in Anderson 1968 and Finklin 1973. It started in the last days of August 1967 and made a major run on 1 September, burning a total area of 22 600 ha. The fire spread on hilly terrain covered by young to mature pine stands with shrub and slash on the ground, with altitudes between 1200 and 2100 m. Data for meteorological conditions are given in both reports.

A table with relevant parameters of fire spread is given for the period between 7.00 and 23:00 hours, with hourly values from 13:00 hours on, during the major run. Indicative ROS values are given for every period from 14:00 until 23:00 hours. These are plotted in Fig. S1 *a*, *b* as a function of time and distance respectively. A graph of the *ROS T1* evolution for Sundance fire is included in Rothermel (1991) as its fig. 1.

In the interpretation of fire spread, Anderson makes use of the three factors (topography, fuels and meteorology) but has difficulty in explaining the decline in fire spread after 18:00 and 22:00 hours. Several explanations are proposed, namely 'because the small fuel size particles were consumed, by steeper slopes, by in-drafts and by lower wind velocity at lower terrain elevations', to justify these ROS reductions. Break down of the fire front due to fuel discontinuities is also pointed out in the report, as well as 'an increase in relative humidity to above critical values late in the fire run, resulting from the advection of a cooler and moister Pacific air mass, helped (together with fuel and topographical factors) in the run's termination'. We can easily identify the involvement of the 'three factors' without a single mention of fire-induced convection.

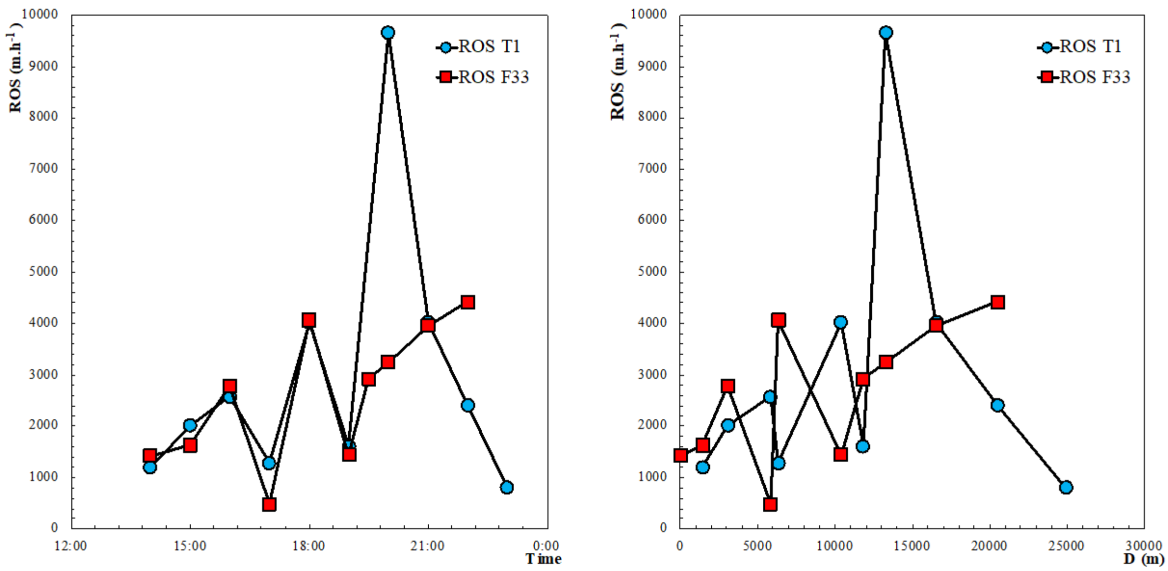
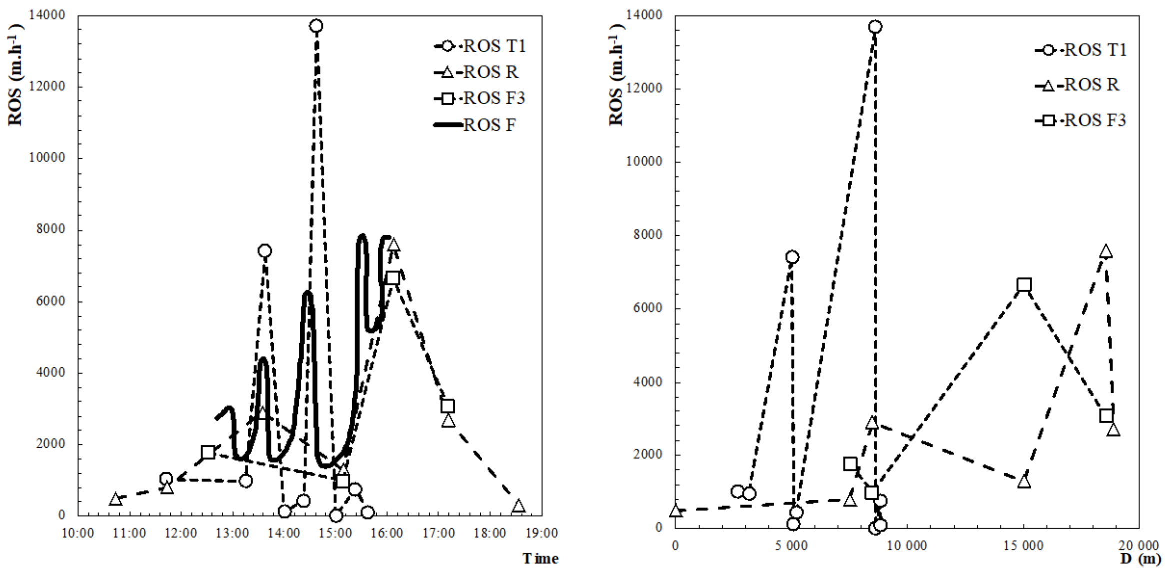


Fig. S1. Analysis of the Sundance Fire: (*a*) Estimated ROS as a function of the Time; (*b*) Estimated ROS as a function of the distance.

Case 2 - Air Force Bomb Range Fire

The fire that started on 22 March 1971 in the Air Force Bomb Range in North Carolina is a very interesting case study in the context of this paper. This fire is well described in Wade and Ward 1973. It spread on flat terrain covered with *Pinus serotina* of ~4–5 m high and a mixture of shrubs. It burned 11 860 ha, most of it in a 4-h run under a very strong wind with an average velocity of 7–9 m s^{-1} and gusts of 18 m s^{-1}. The fire had a pulsating behaviour with at least three observed peaks of ROS followed by periods with the formation of strong convection columns. In table 1 of that report a description of the fire evolution is given. The ROS of the head fire during given periods of time are provided and these are plotted in our Fig. S2 as *ROS T1*. In fig. 3 of that report, an aerial photo with the overall evolution of the fire is given with the position of the head fire marked on the map; from this figure we derived the distance *Dis F3* and the *ROS F3*. Figure 10 of the report provides an interpretation of the oscillating character of the fire and proposes the mechanism of short distance spotting to justify the variations in the ROS during the initial hours of the fire run. Although this figure is only a sketch, we used it to estimate the distance *Dis F10* and the average values of the *ROS F10*. In their figure 11, Wade and Ward plot the variation of intensity of the fire during the first 4 h of its run. This curve shows at least four peaks of fire line intensity, each one larger than the previous one. Given its interest for the present analysis we converted the fire line intensity into ROS values assuming an average consumed fuel load of 2.6 kg m^{-2} and a heat release value of 2780 cal g^{-1}, according to the data provided in the paper. In Fig. S2, the corresponding ROS is designated as *ROS F11*.



a) b)

Fig. S2. Analysis of the Air Force Bomb Range Fire: (*a*) Distance travelled by the fire according to figures 3 and 10 of the Report; (*b*) Estimated ROS according to table 1, figures 3, 10 and 11 of the Report.

In Fig. S2 *a*, *b*) respectively the values of the distance travelled by the fire and the ROS estimated from the various sources mentioned above are presented. The distance *Dis F3* agrees well with *Dis F10*, which is more detailed during the initial hours. Correspondingly, the *ROS F3* estimated from Fig. S3 and *ROS T1* show good agreement. On the other hand, *ROS F10* and *ROS F11* have more detail in the initial period but they do not show very good agreement.

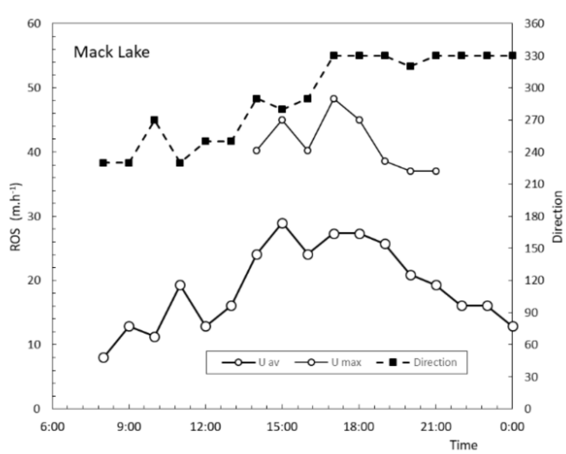
This case illustrates the relevance of accurately documenting and reporting the evolution of a fire, which is certainly very difficult in the case of very large fires like this one. In spite of the discrepancies found in the analysis, it is very clear that this fire had oscillatory behaviour and the authors discuss this behaviour very carefully, proposing several hypotheses to explain it. More details can be found in the report.

Case 3 - Mack Lake Fire

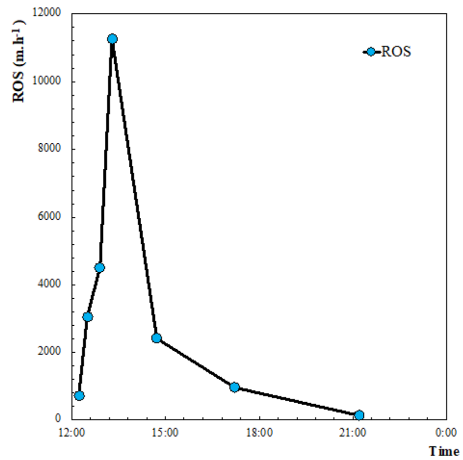
The Mack Lake fire occurred on the 5 May 1980 near Mio, Michigan, USA, burned ~9700 ha, destroyed 44 houses and claimed one life (cf. Simard *et al.* 1983). The fire burned mainly *Pinus banskiana* overstorey, on a fairly flat plateau. The fire started with a prescribed burn initiated by 10:26 hours that escaped at 12:06 hours and initiated a very rapid run until ~13:30 hours. Wind velocity during this period was of the order of 60–90 km h^{-1} with gusts up to 130 km h^{-1}, as shown in Fig. S3*a*). During the day wind was blowing from the west and turned to the NW, but during the major run, it varied between 240º and 280º. Distances travelled by the fire and ROS are given in tabular form and as a fire growth map in Simard *et al.* 1983. These data are plotted in Fig. S3 *b*) and show clearly that the fire accelerated until 13:30 hours reaching an average ROS of 9.7 km h^{-1} between 13:10 and 13:25 hours. After this run the ROS dropped dramatically until 16:00 hours to 2.2 km h^{-1} and this cannot be explained by a sudden change of wind velocity or any other factor rather than the modification of the flow field created by the fire, as proposed in the present model.

The authors of the report discuss five hypotheses to justify the behaviour of the fire. These include a fluctuation in wind direction, wind speed decrease, burnout of part of the vegetation, backfire from pockets of unburned fuel and the distribution of firebrands. Those authors are in favor of the last hypothesis.

(a)



(b)



(c)

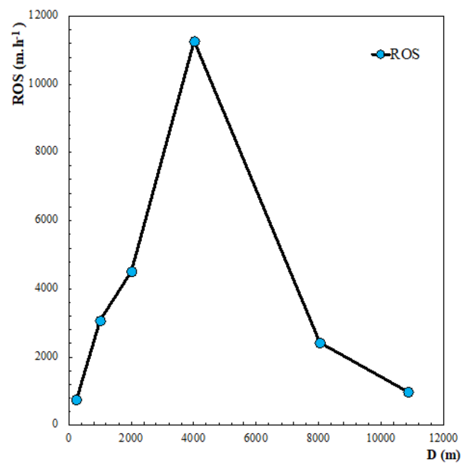


Fig. S3. Analysis of Mack Lake Fire: (*a*) Wind velocity and direction; (*b*) estimated ROS as function of the time; (*b*) estimated ROS as function of distance travelled by the fire.

Case 4 - Butte Fire

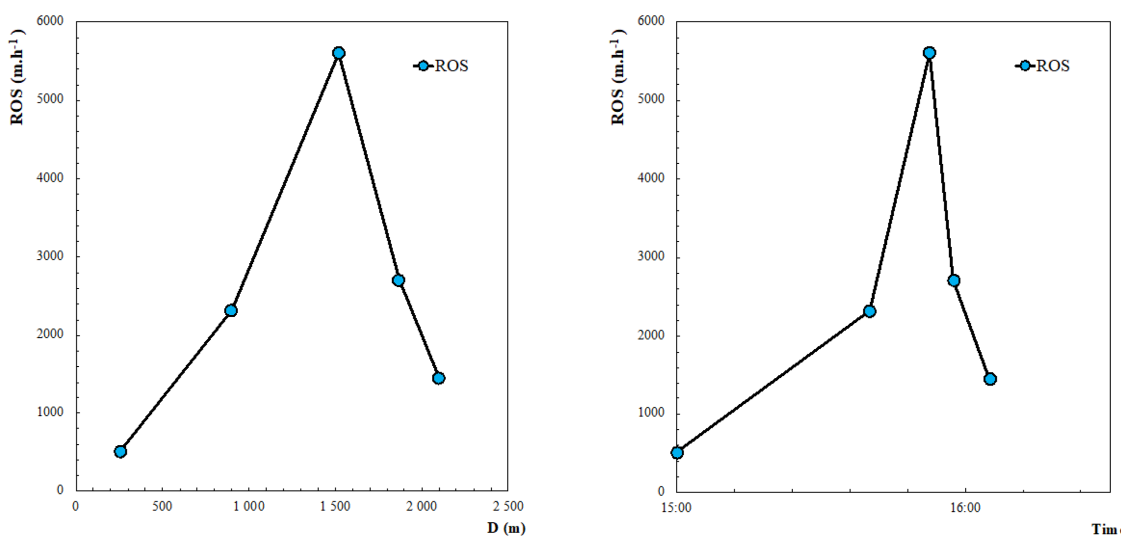
This fire occurred on 29 August 1985 in the Salmon National Park, Idaho, USA. A report on this fire is given in Rothermel and Mutch (1986). This fire was actually part of a complex of fires that started in the region by lightning on 20 August and were being monitored and contained. In the afternoon of 29 the fire made a very intense run in less than 2 h, forcing 73 firefighters to take to their shelters in safety areas in order to survive the passage of the fire, making it a very important case study for fire shelter use. The weather on that day was normal for the period, with a temperature above 25ºC and wind of the order of 12–19 km h^{-1}, with gusts of more than 30 km h^{-1}. Between 14:30 and 15:30 hours, before the essentially South to North run along the Wallace

Creek basin began, the ROS was ~500 m h^{-1}, but later it increased to an average of 3 km h^{-1} with an estimated maximum of 5.6 km h^{-1}, according to the report (Fig. S4).

In the report, the authors say that: ‘As with any fire, this one must have moved by surges, with some periods of little or no spread. Reconstructed spread rates are too coarse to show the surges and appear to be slower than the impression received by the observers on the ground’. This statement is interesting because it recognizes that the fire spread is made in surges, which is equivalent to our interpretation of intermittent or oscillatory fire behaviour. On the other hand, it admits that the available data cannot describe in detail the full behaviour of the fire, as the averaging process of the analysis tends to smooth the oscillations of fire spread.

One other interesting observation made in the report is based on what the firefighters experienced in the period of ~1 h in which they were in their shelters. The firefighters reported that they felt three waves of fire, the first one from the SE (the approach of the main fire), then a second from the N (the back flow induced by the fire) and a third one from SW (after the passage of the fire).

When the column of the fire passed near the shelter area it was described as having flames more than 50 m long, with large balls of flame in the air and very strong and turbulent winds that would almost carry the men floating in the air.



(a) (b)

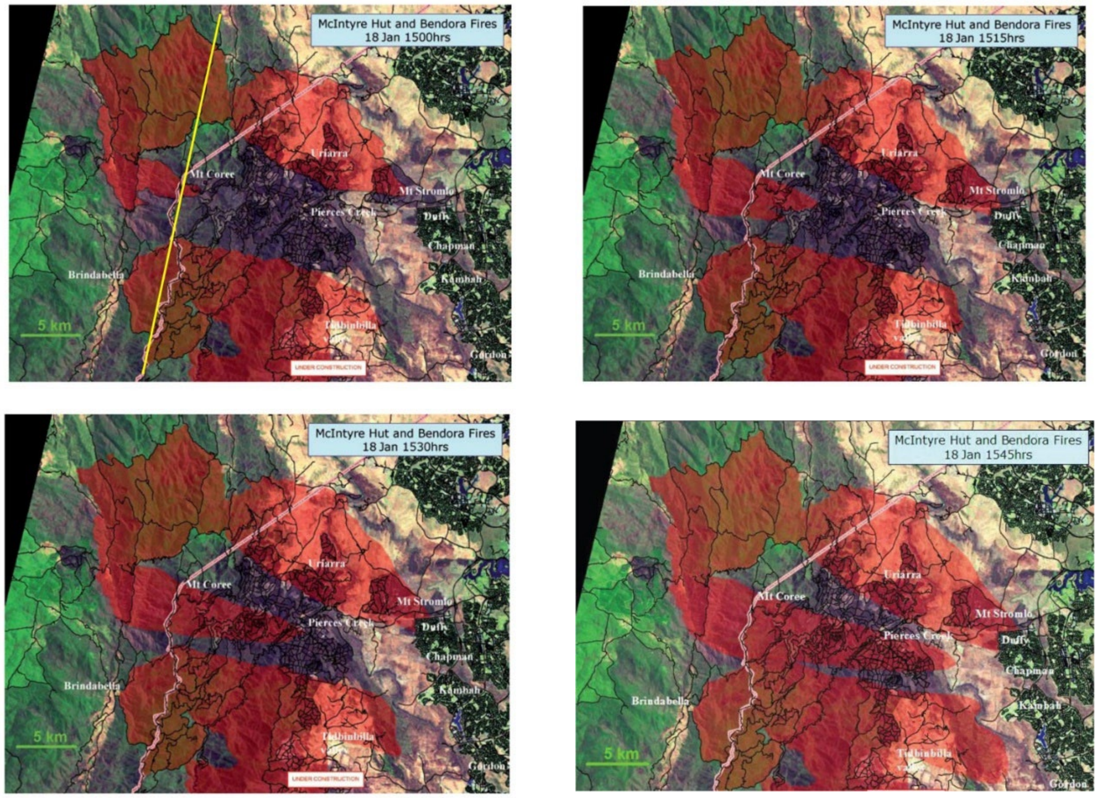
Fig. S4. Evolution of the advance and ROS of the head of the Butte Fire on 29 August 1985: (*a*) estimated ROS as function of the distance travelled by the fire; (*b*) estimated ROS as function of the time.

Analysing the behaviour of the fire the authors of the report recognize that weather conditions would not have contributed to the large-scale convection activity that was observed; on the other hand, they attribute the upslope runs to the terrain configuration. Interestingly the authors attribute the formation of the convection column to the ‘heavy surface fuels (that) proved to be a juxtaposition capable of generating an incredible amount of energy in a short time’. As usual no mention is made of fire generated convection and how it modified the ambient flow and therefore the behaviour of the fire.

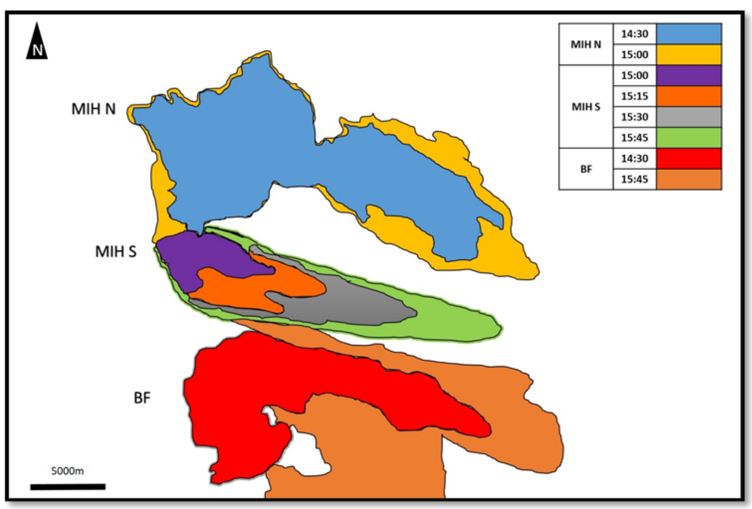
Case 5 – Canberra Fire

On 8 January 2003, lightning storms affected the Australian Capital Territory (ACT), to the north of Canberra, creating several fires. Eventually, the various ignitions combined in two main fires, the MacIntyre Hut Fire and Bendora Fire. On 18 January, these fires moved in a parallel direction towards Canberra as two merging fire fronts and caused four deaths, the destruction of part of the city of Canberra and several hectares of burned land. According to testimonies and ground evidence (cf. ACT Coroners court 2006), fire spread associated with these merging fires was very fast, and a tornado was formed ahead of the advancing fire front in the space between the two main fires. This episode occurred in a situation characterised by: non-flat terrain, non-uniform vegetation cover, very strong wind and the influence of two very intense fires. Between the flanks of Bendora and McIntyre Hut’s that were spreading on undulating ground covered by grass, shrubs and groups of trees under a strong wind of the order of 25 m s^{-1}, a third fire was formed by the convection induced by the two main fires like in the Junction fire cases as shown in Fig. S5. More details on this fire can be found in Sharples *et al.* (2012).

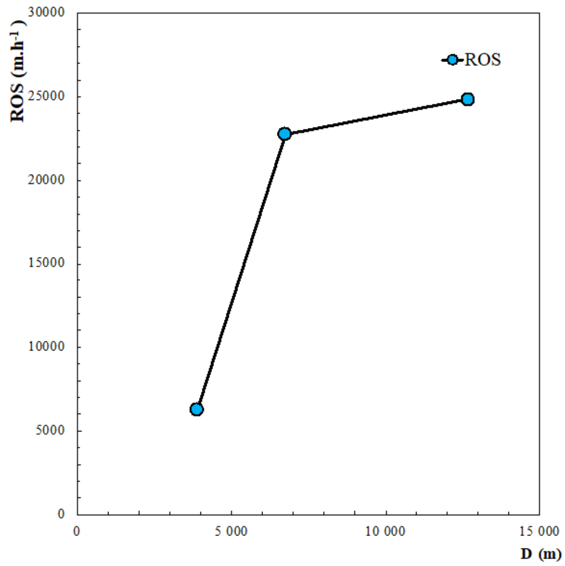
(a)


McIntyre Hut and Bendora Fires
18 Jan 1500hrs
McIntyre Hut and Bendora Fires
18 Jan 1515hrs
McIntyre Hut and Bendora Fires
18 Jan 1530hrs
McIntyre Hut and Bendora Fires
18 Jan 1545hrs
Mt Coree
Uriarra
Mt Stromlo
Pierces Creek
Duffy
Chapman
Kambah
Brindabella
Tidbinbilla valley
Gordon
5 km

(b)


N
MIH N
MIH S
BF
MIH N 14:30
15:00
MIH S 15:00
15:15
15:30
15:45
BF 14:30
15:45
5000m

c)



d)

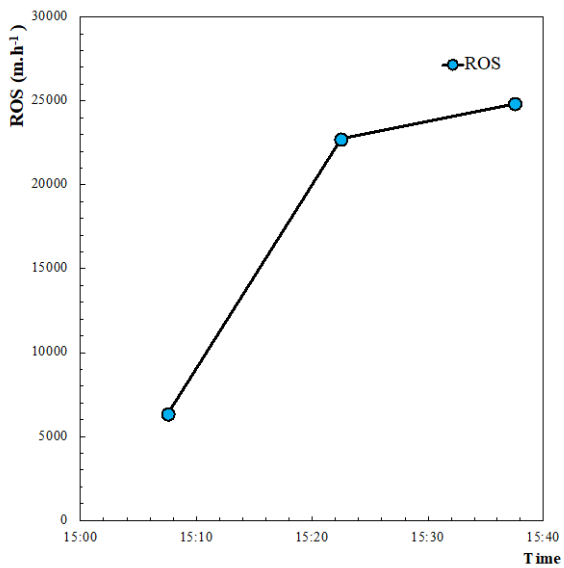
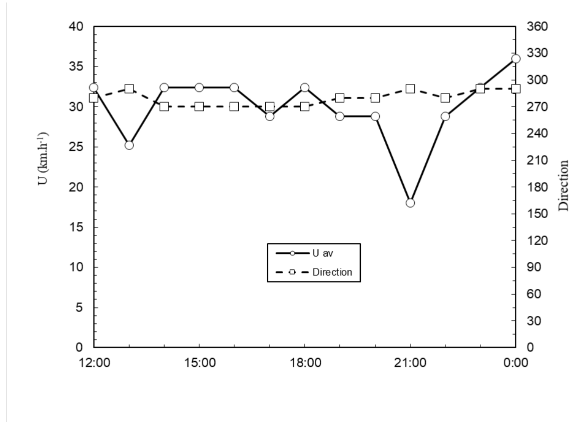


Fig. S5. (*a*) Evolution of McIntyres Hut and Bendora fires on 18 January between 15:00 and 15:45 hours. Plates from Cheney (2004); (*b*) isochrones of the fire propagation; (*c*) estimated ROS as function of the distance travelled by the fire; (*d*) estimated ROS as function of the time.

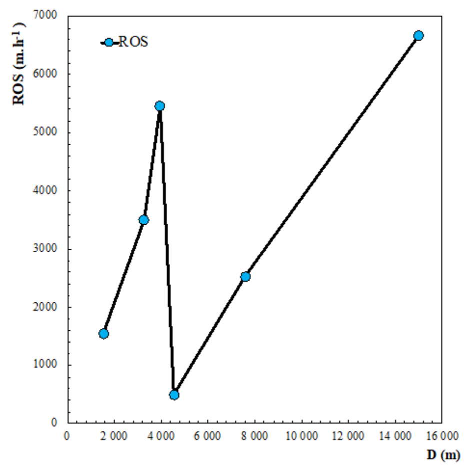
Case 6 - Vidauban Fire

The Vidauban fire (France) occurred in the afternoon of 17 July 2003 and spread along 22 km during 7 h consuming 6744 ha. Alexandrian (pers. Comm. 2004) reported that the wind at the station of St Raphael during the period of the fire was almost constant with a velocity of the order of 30 km h^{-1} and blowing from WNW as shown in Fig. S6 *a*). The terrain in which the fire spread was undulating ground covered by pine trees and descending from 600 to 50 m in the direction of the Mediterranean Sea. The fire had two

(a)



(b)



(c)

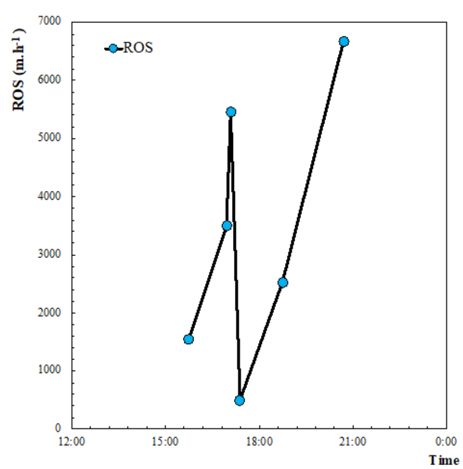


Fig. S6. (*a*) Data on the wind velocity and direction in the Vidauban region on 17 July 2003; (*b*) ROS of the head fire as function of the distance travelled by the fire; (*c*) ROS of the head fire as function of time.

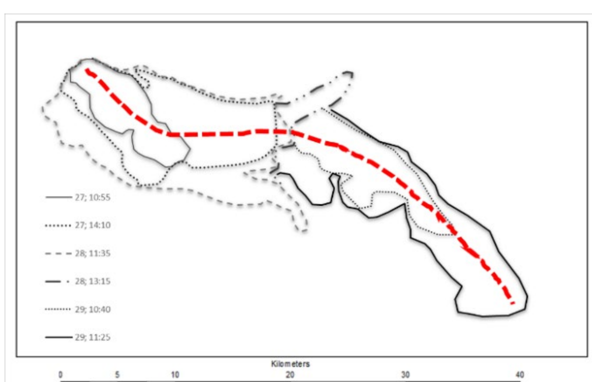
major runs with an intermediate period in which the very strong spotting that was produced at the end of the first period consolidated in a large mass fire, which then accelerated until it reached a ROS of the order of 6.7 km h^{-1}. After 17:00 hours it reduced its ROS until 18:00 hours, then it resumed its propagation with two acceleration periods until 22:00 hours. In Fig. S6 *b*, the distance travelled by the head fire and its average ROS during the observation periods are shown.

Case 7 - Almodôvar Fire

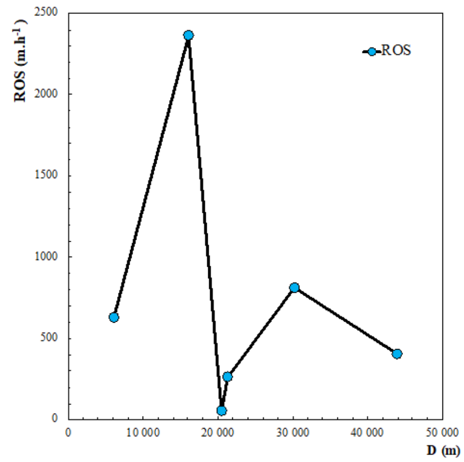
The Almodôvar fire developed in the South of Portugal and is described in Palrilha et al. (2004). It started on 26 September 2004 at ~15:30 hours and was extinguished on 30 September, burning a total of 28 600 ha. The terrain is hilly with altitudes between 150 and 600 m and covered with *Quercus suber*, *Quercus oak,* pine, eucalyptus and several types of shrubs. Hourly wind direction and velocity from the nearby station of S. Brás de Alportel, indicated that from 26 September to midday on 30 September, the wind direction was almost constant and from the NW (between 300 and 330º). The wind velocity was between 16 and 8 km h^{-1} on 26 then decreased to 4 km h^{-1} during 27 and 28 September. On 29 September, it increased to values of the order of 10–15 km h^{-1}. After 12:00 hours it decreased practically to zero at 24:00 hours.

The reconstruction of the evolution of the fire perimeter is shown in Fig. S7 *a*. From this analysis we estimated the distance travelled by the head of the fire and the average ROS since its start at 15:30 hours. The fire travelled nearly 50 km in 4 days spreading practically from West to East during the first 2 days and then deflecting to the SE during the following days. On the first day, the fire had a dramatic acceleration; then it abated and had a second cycle of ROS variation on the last two days, as can be seen in Fig. S7 *b*.

a)



b)



c)

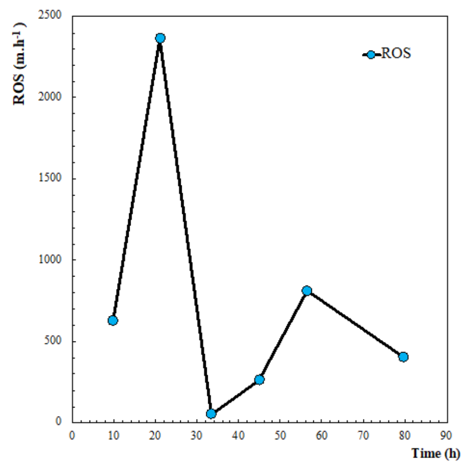


Fig. S7. (*a*) Isochrones of the Almodôvar Fire in September 2004; (*b*) Evolution of the ROS as a function of the distance travelled by the fire; and (*c*) ROS of the head fire as function of time since the fire start at 15:30 hours on 26 September 2004.

Case 8 - Carmel Fire

The fire that occurred on Mount Carmel in Israel on 2 December 2010 will be always remembered by the dramatic loss of 45 lives that it caused few hours after it started in the early afternoon of that day. On the following day the fire continued to spread under strong wind in the direction of the Mediterranean Sea, near the city of Haifa. We had access to a series of photographs taken from a police helicopter flying over the area of the fire at ~1200 m altitude, which provided the sequence of images shown in Fig. S8. In these photos, taken between 12:59 and 13:29 hours, we can see that a section of the flank of the fire starts to spread rapidly under a relatively strong wind (cf. Kutiel 2013), forms a convection column that becomes vertical and then dissipates. The fire travelled on undulating ground descending towards the sea covered by small trees and shrubs. Using a terrain map and the photos, it was possible to estimate the distance travelled by the head of this fire section and to estimate its ROS as shown in Fig. S9 *a*. Hourly wind data measured at the University of Carmel AWS on 3 December 2010 are shown in Fig. S9 *b*). As can be seen, the wind direction was practically constant from the SE; the velocity was also constant and ~9 m s^{-1} with gusts between 12 and 14 m s^{-1}. The observed changes in the wind velocity do not explain the increase of the ROS and especially the recorded sudden decrease. In our opinion, this well documented case of a 30 min duration fire event confirms entirely the conceptual model proposed.

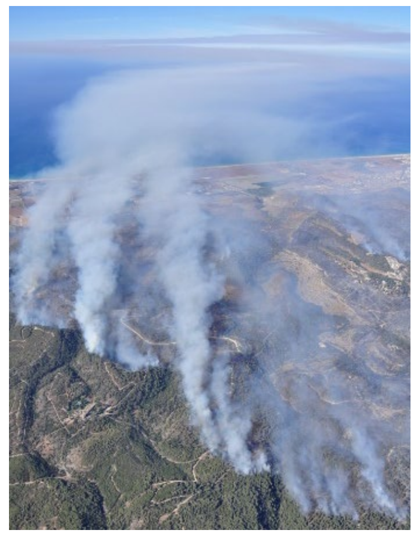
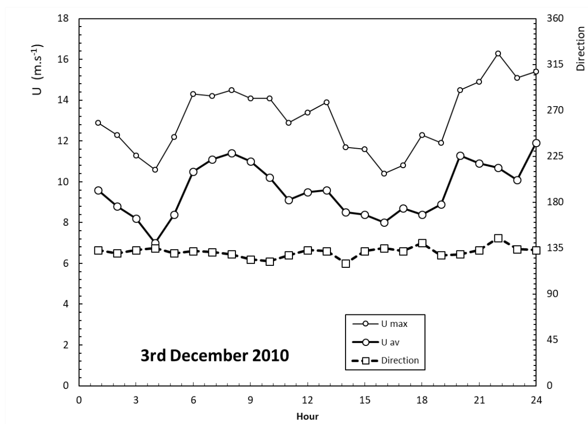
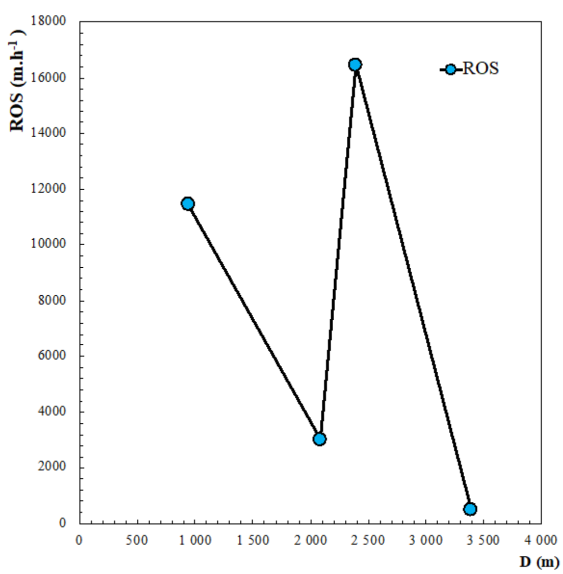


Fig. S8. A sequence of images taken from a section of the Carmel Fire near the city of Haifa on 3 December 2010.

a)



b)



c)

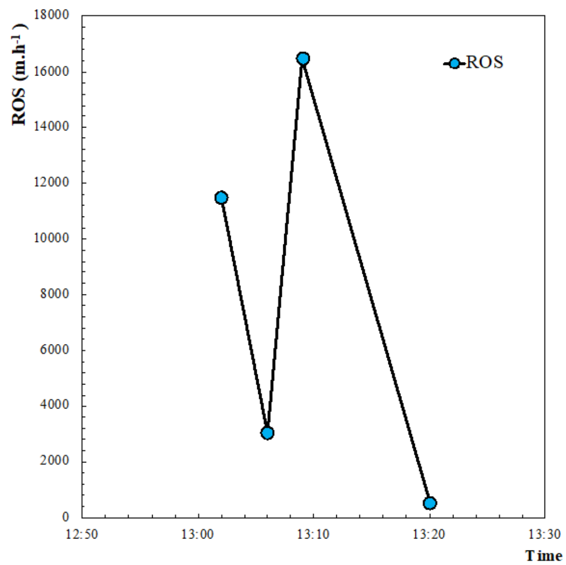


Fig. S9. (*a*) Data on the wind velocity and direction in the Haifa region on 3 December 2010; (*b*) ROS of the head fire as function of the distance (D) travelled by the fire; (*c*) ROS of the head fire as function of time.

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