Universidade de Coimbra

European Commission (EC)
GOFC GOLD Fire Implementation Team (GOFC Fire IT)

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Analysis of Extreme Fire Behaviour

Domingos Xavier Viegas
Departament of Mechanical Engineering
University of Coimbra
xavier.viegas@dem.uc.pt

1 Introduction

- In this lecture I will present the results of our current research on **Extreme Fire Behaviour** (EFB). I will show that the behaviour of a fire is a time dependent process, dominated by its boundary conditions and by its own dynamics due to its interaction with the atmosphere.

- The ROS of the head of the fire changes in an oscillatory motion with an amplitude that increases with the average ROS.

- In some cases the fire accelerates and reaches very high values of ROS and consequently of fireline intensity.

b. Extreme Fire Behaviour

- When we speak about **Extreme Fire Behaviour** we refer to some out of normal process of fire behaviour.
- Among the many possible definitions I mention one that I proposed in 2012.

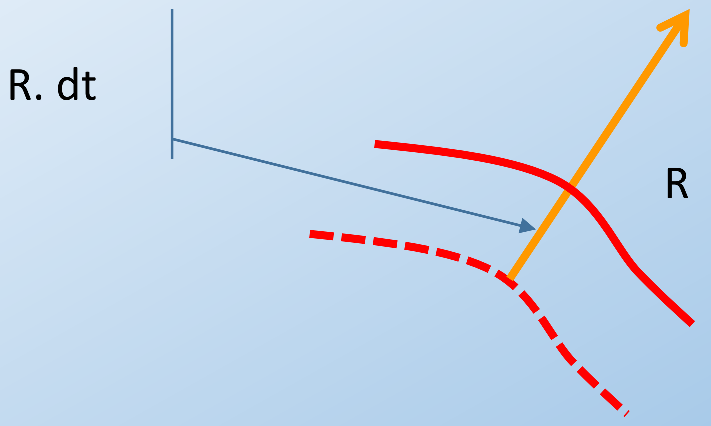
*"**Extreme Fire Behaviour** is the set of forest fire spread characteristics and properties that preclude the possibility of controlling it safely using available present day technical resources and knowledge"*

Viegas, D.X., 2012. Extreme Fire Behaviour. In: Armando C. Bonilla Cruz and Ramona E. Guzman Correa (Ed.), *Forest Management: Technology, Practices and Impact*. Nova Science Publishers, Inc. ISBN 978-1-62081-359-1.pp: 1-56.

c. Fire behaviour properties

- From the various parameters that characterize the spread of a fire we shall retain the rate of spread (ROS) of the head of the fire as its main descriptor.

Instantaneous value



$$R = \lim_{dt=0} \frac{dx}{dt}$$

Fireline Intensity

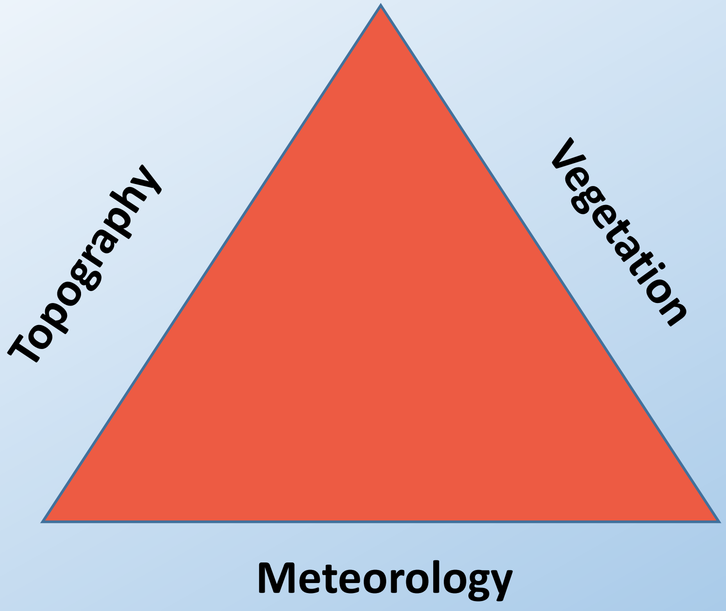
A very important property related to the ROS is the Fireline intensity (FLI) first proposed by Byram, which is defined by:

$$I = R.Q.M_c$$

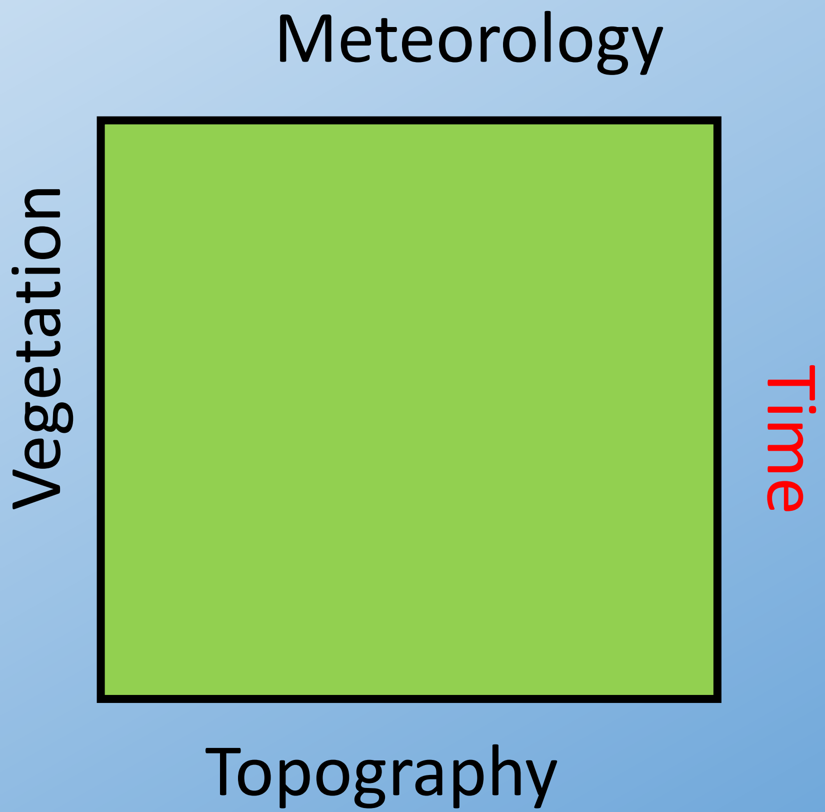
R	ROS	m/s	[0.001 to 10 m/s]
Q	Calorific power	J/kg	[17 to 23 MJ/kg for wood]
M^*_c	Effective fuel load	kg/m^2	[0.3 to 6 kg/m^2].

b. Factors affecting surface fire spread

Triangle of fire factors



Square of fire factors



Topography

- Slope

Characterized by slope angle αº

- Curvature or concavity

Vegetation

- H_f Fuel depth (m)
- M_c Fuels load (kg/m^2)
- β Compactness (-)
- x,y,z Composition of the fuel bed in species, dead and live fuels, size classes
- σ Equivalent surface to volume ratio (m^{-1})
- t_o Residence time
- m_f Equivalent fuel moisture content (%).

Among these parameters the fuel moisture content plays a very important role, so we will mention it frequently.

Meteorology

- Wind velocity, direction and gustiness;
- Vertical stability of the atmosphere.

- The local wind at the fire will be:

$$\vec{U} = \vec{U}_o + \vec{U}_f$$

c. Static Fire Behaviour

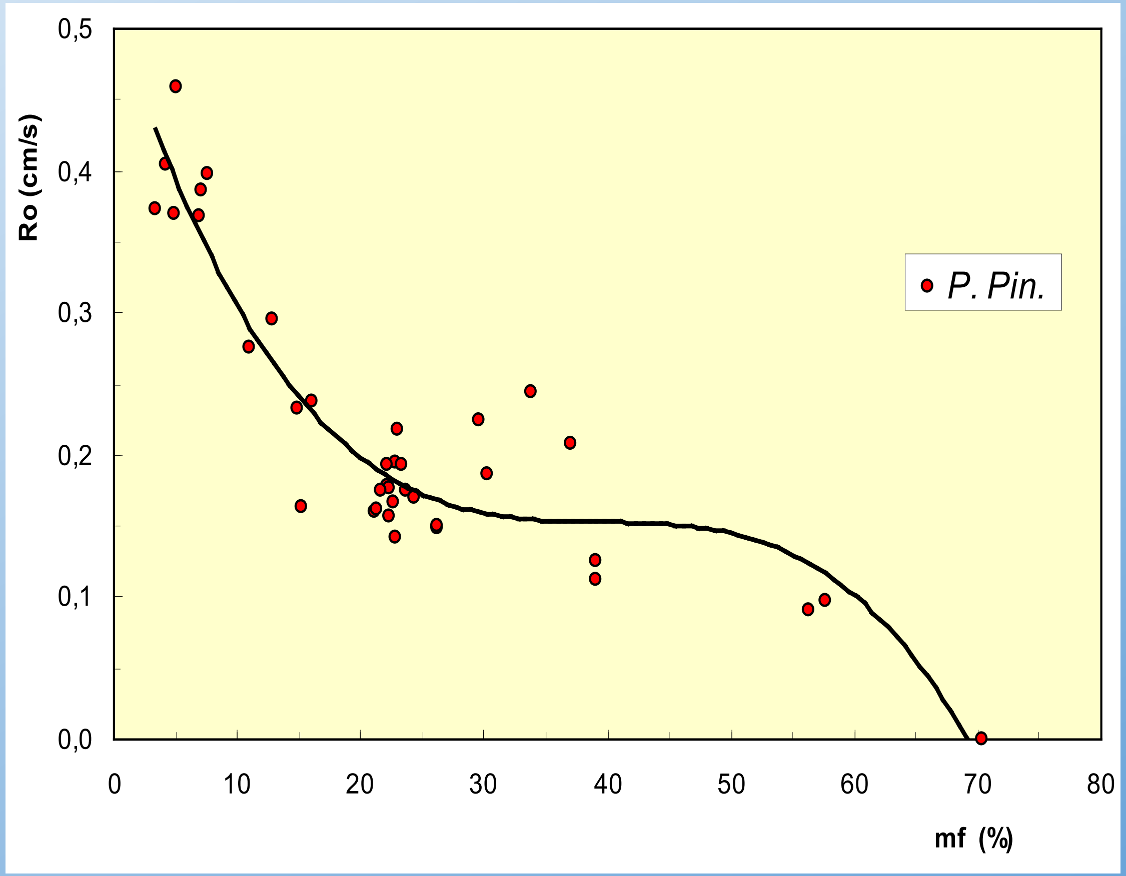
- According to the Rothermel Model (1972) the local ROS at a given point of the fire front is given by the local properties of the determining factors.

$$R = f(\sigma, \alpha, U).R_o = (1 + \phi_s + \phi_w).R_o$$

- The model parameters depend on fuel, terrain slope and ambient wind velocity.

Basic ROS

- A characteristic property of a fuel bed is its <u>Basic ROS</u>, R_o , in the absence of slope or wind.



Non-dimensional ROS

- We define the non-dimensional ROS R' by:

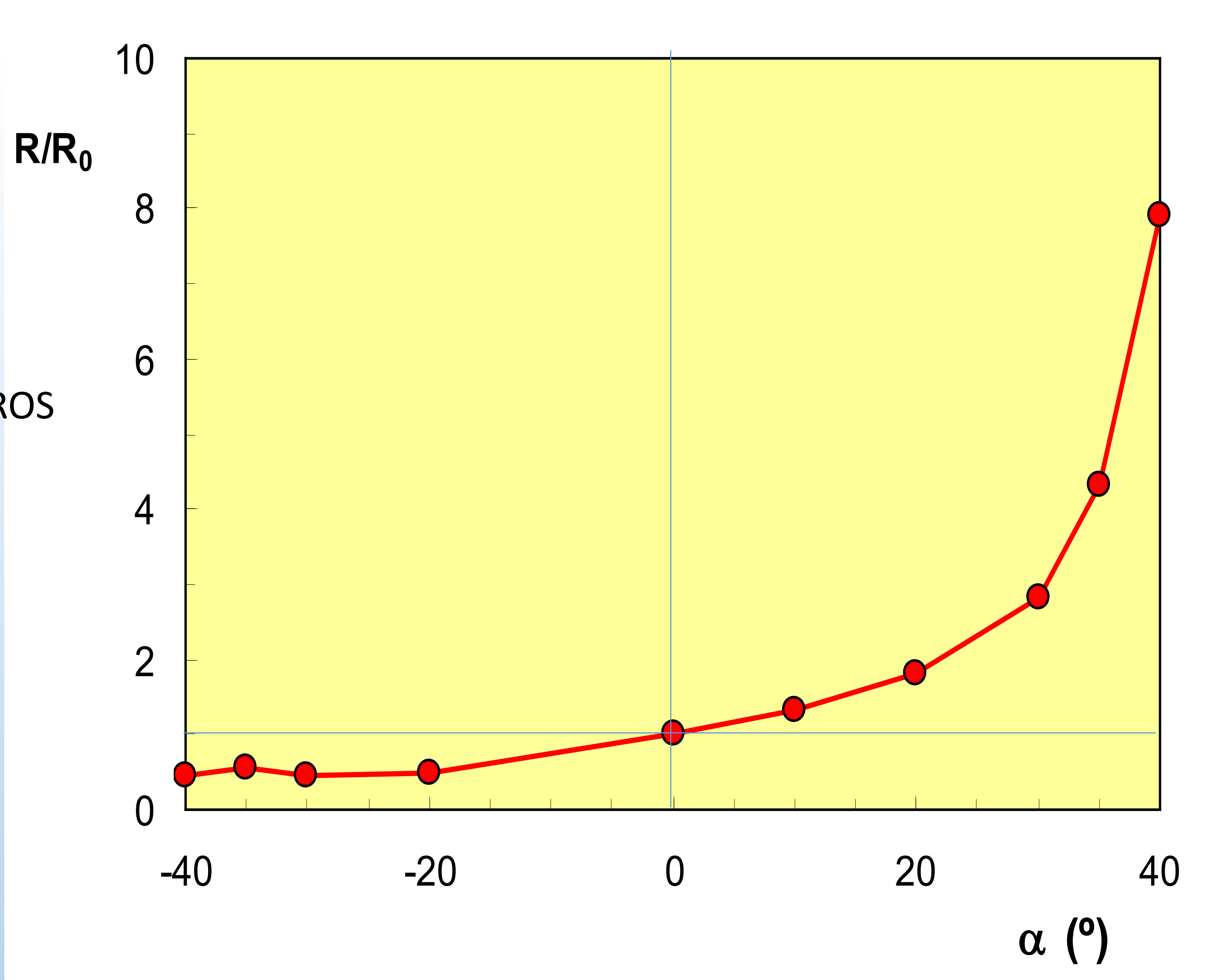
$$R' = \frac{R}{R_o}$$

$$R = f(\sigma, \alpha, U).R_o = (1 + \phi_s + \phi_w).R_o$$

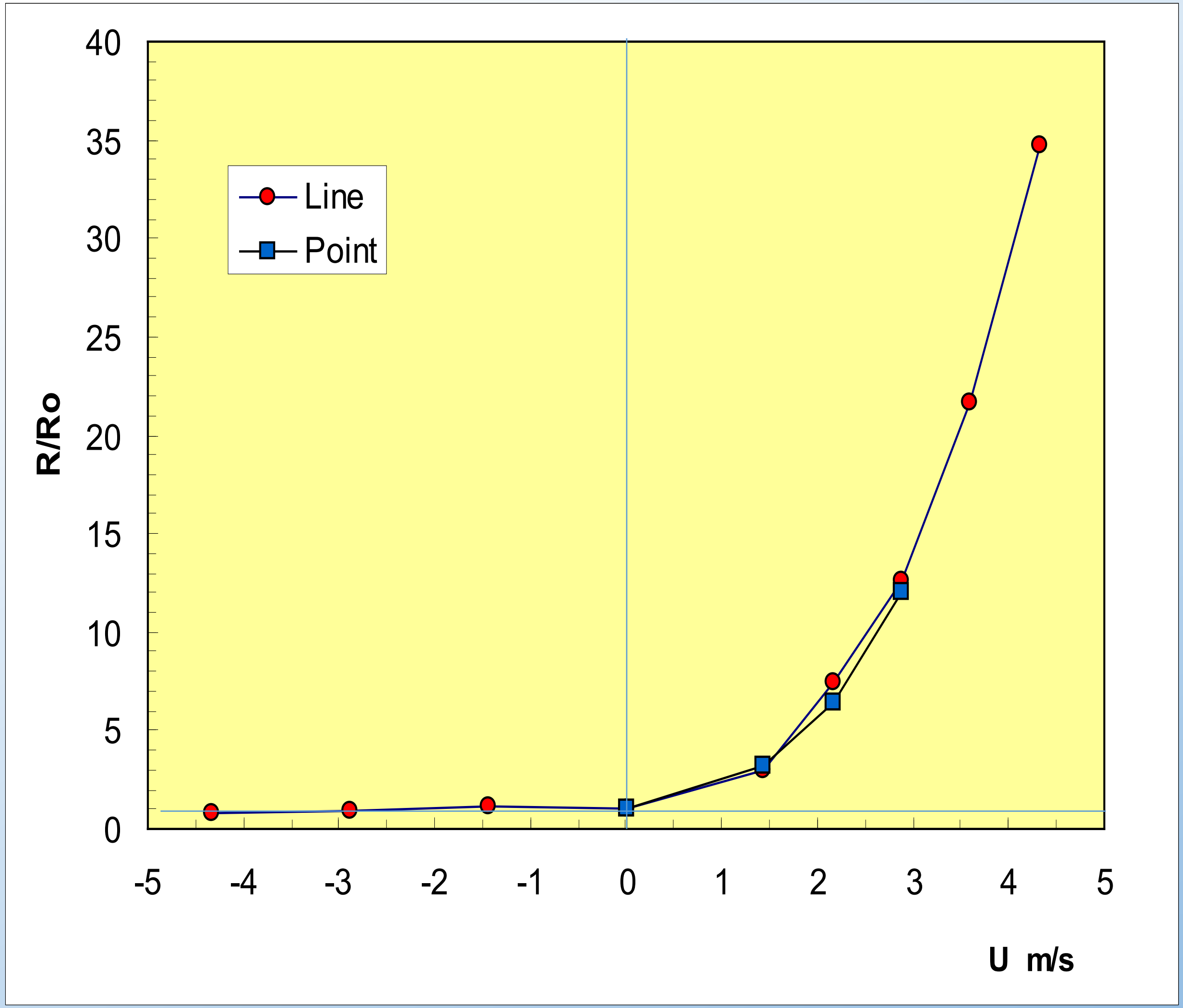
$$\frac{R}{R_o} = f(\sigma, \alpha, U) = (1 + \phi_s + \phi_w)$$

Effect of Terrain Slope on the Average ROS

Average ROS



Effect of Wind Velocity on the Average ROS



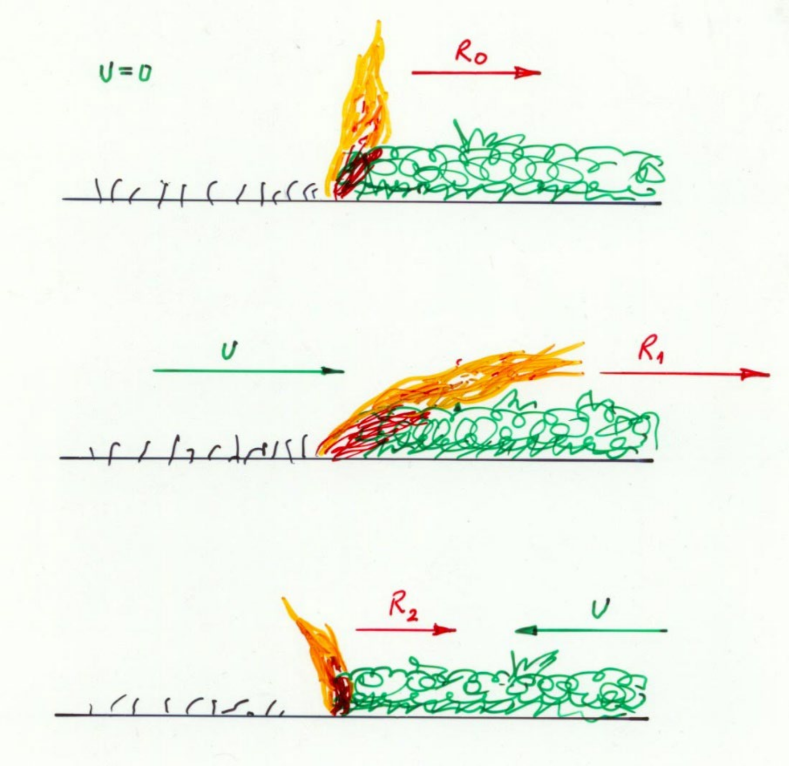
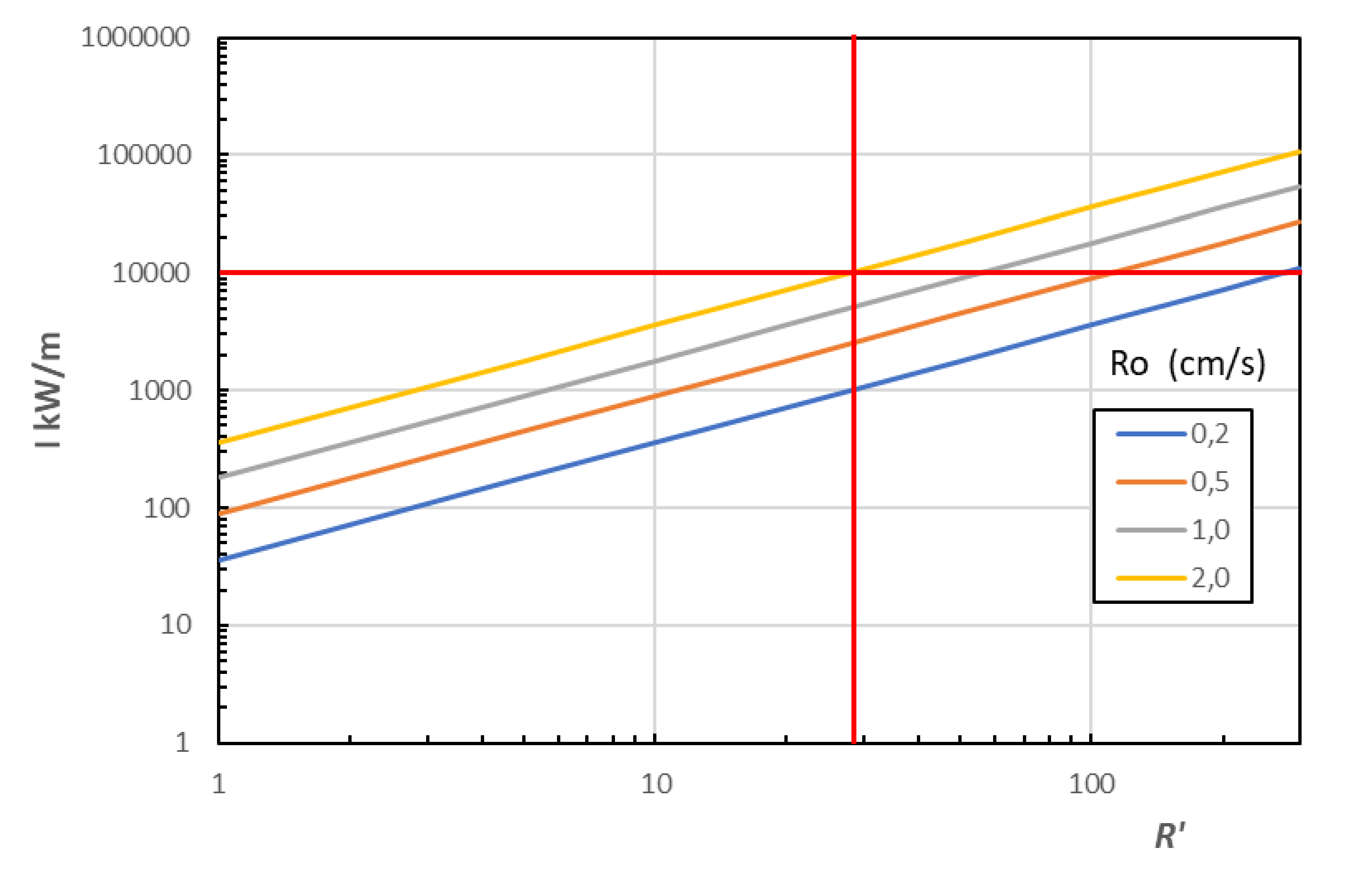


Table 3. Wildfire events classification based on fire behavior and capacity of control.

Fire Category		Real Time Measurable Behavior Parameters			Real Time Observable Manifestations of EFB				Type of Fire and Capacity of Control *
		FLI* (kWm^{-1})	ROS (m/min)	FL (m)	PyroCb	Downdrafts	Spotting Activity	Spotting Distance (m)	
Normal Fires	1	<500	<5 [a] <15 [b]	<1.5	Absent	Absent	Absent	0	Surface fire Fairly easy
	2	500–2000	<15 [a] <30 [b]	<2.5	Absent	Absent	Low	<100	Surface fire Moderately difficult
	3	2000–4000	<20 [c] <50 [d]	2.5–3.5	Absent	Absent	High	≥100	Surface fire, torching possible Very difficult
	4	4000–10,000	<50 [c] <100 [d]	3.5–10	Unlikely	In some localized cases	Prolific	500–1000	Surface fire, crowning likely depending on vegetation type and stand structure Extremely difficult
Extreme Wildfire Events	5	10,000–30,000	<150 [c] <250 [d]	10–50	Possible	Present	Prolific	>1000	Crown fire, either wind- or plume-driven Spotting plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Chaotic and unpredictable fire spread Virtually impossible
	6	30,000–100,000	<300	50–100	Probable	Present	Massive Spotting	>2000	Plume-driven, highly turbulent fire Chaotic and unpredictable fire spread Spotting, including long distance, plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Impossible
	7	>100,000 (possible)	>300 (possible)	>100 (possible)	Present	Present	Massive Spotting	>5000	Plume-driven, highly turbulent fire Area-wide ignition and firestorm development non-organized flame fronts because of extreme turbulence/vorticity and massive spotting Impossible

Note: [a] Forest and shrubland; [b] grassland; [c] forest; [d] shrubland and grassland; *FLI classes 1–4 follow the classification by Alexander and Lanoville [125].

$$I = R.Q.M_c$$



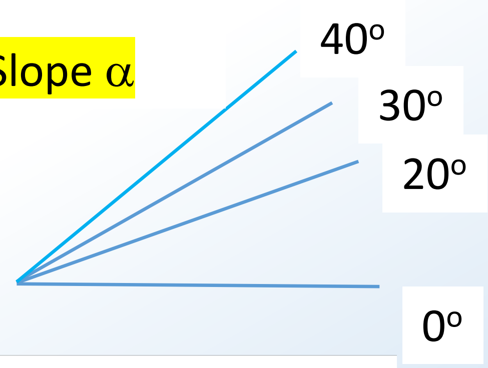
$R = R' x R_o$

$M_c = 1 kg/m^2$

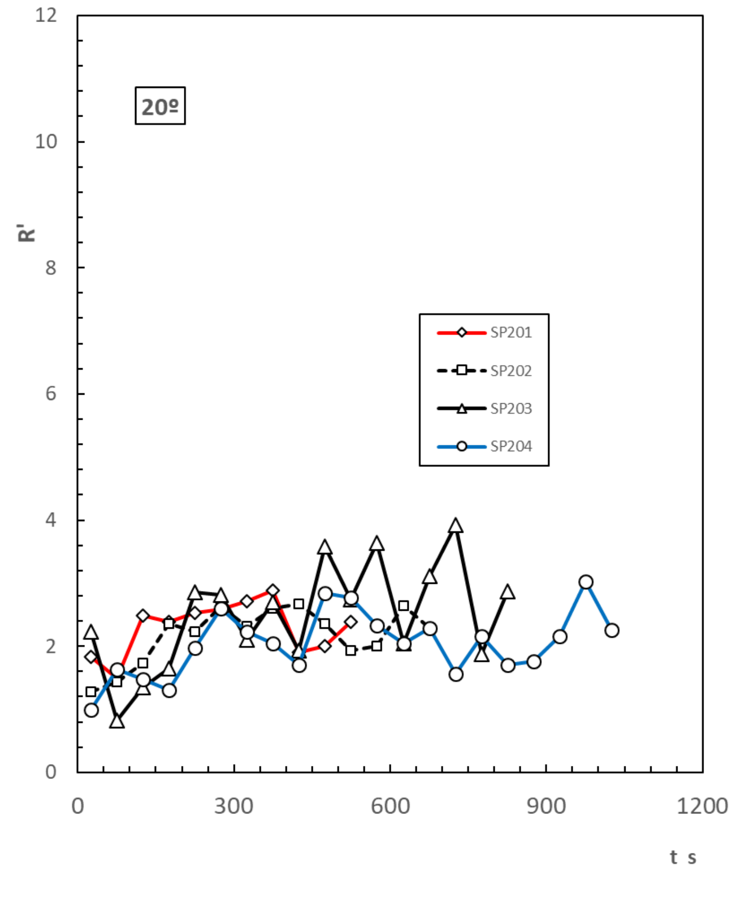
d. Dynamic Fire Behaviour

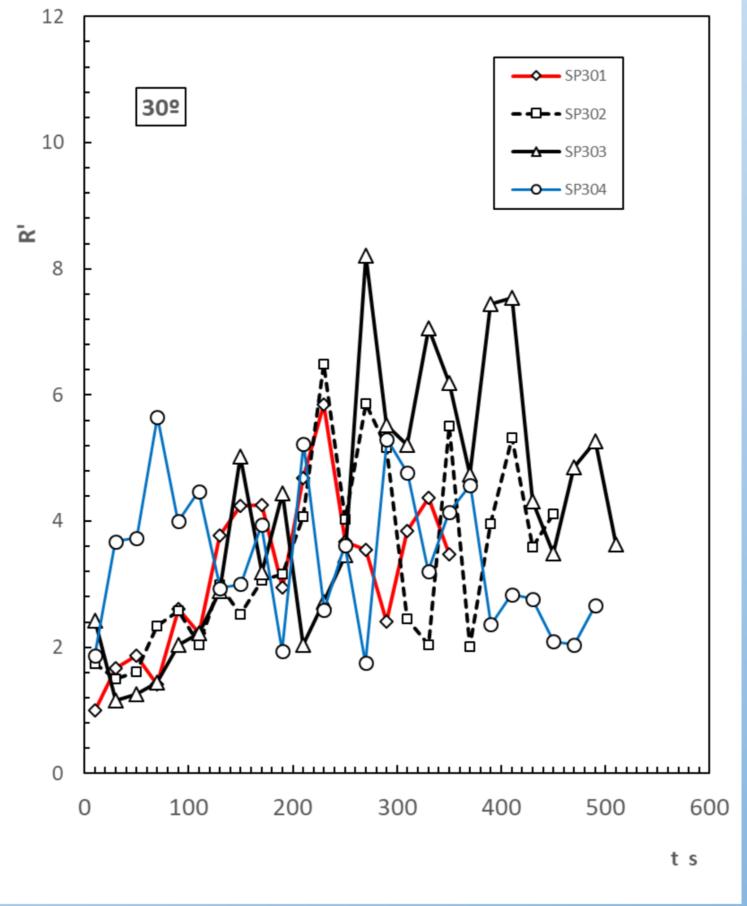
Viegas DX, 2004. On the existence of a steady state regime for slope and wind driven fires. Int. J. Wildland Fire. 13:101-117.

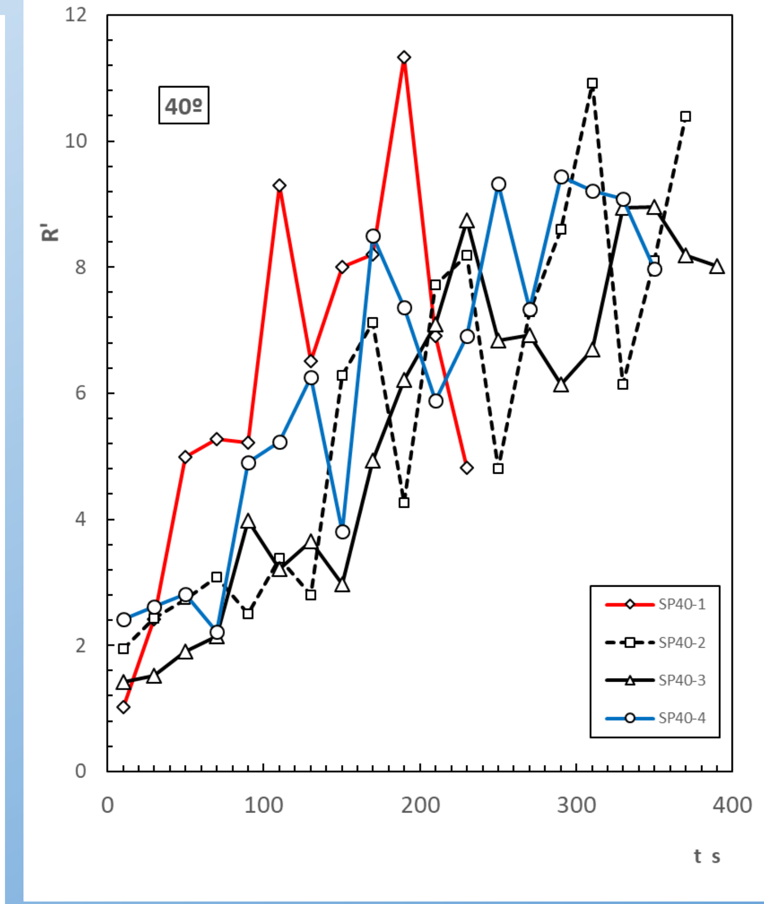
Slope α



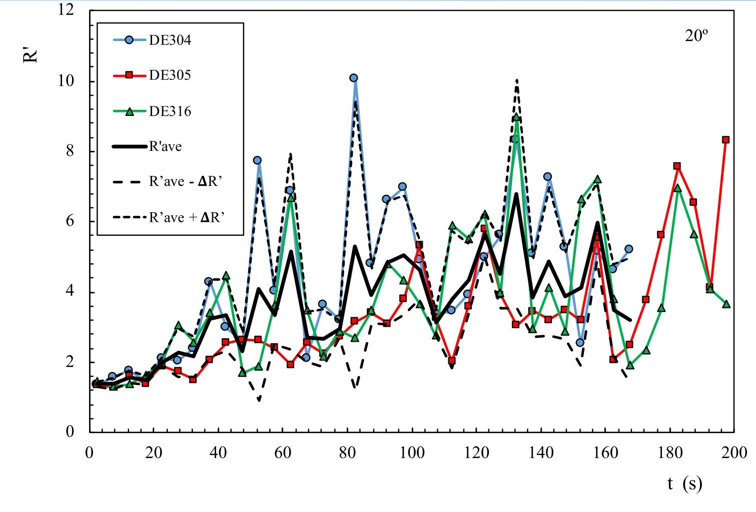
Results of tests of point ignition fires on a slope



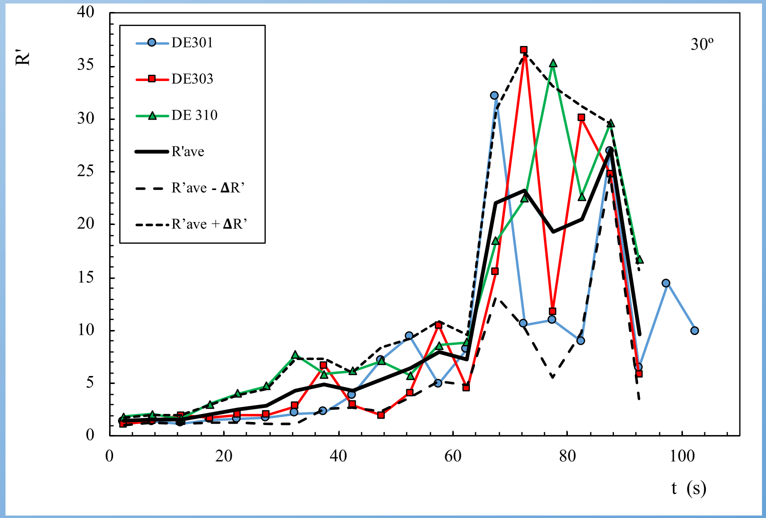




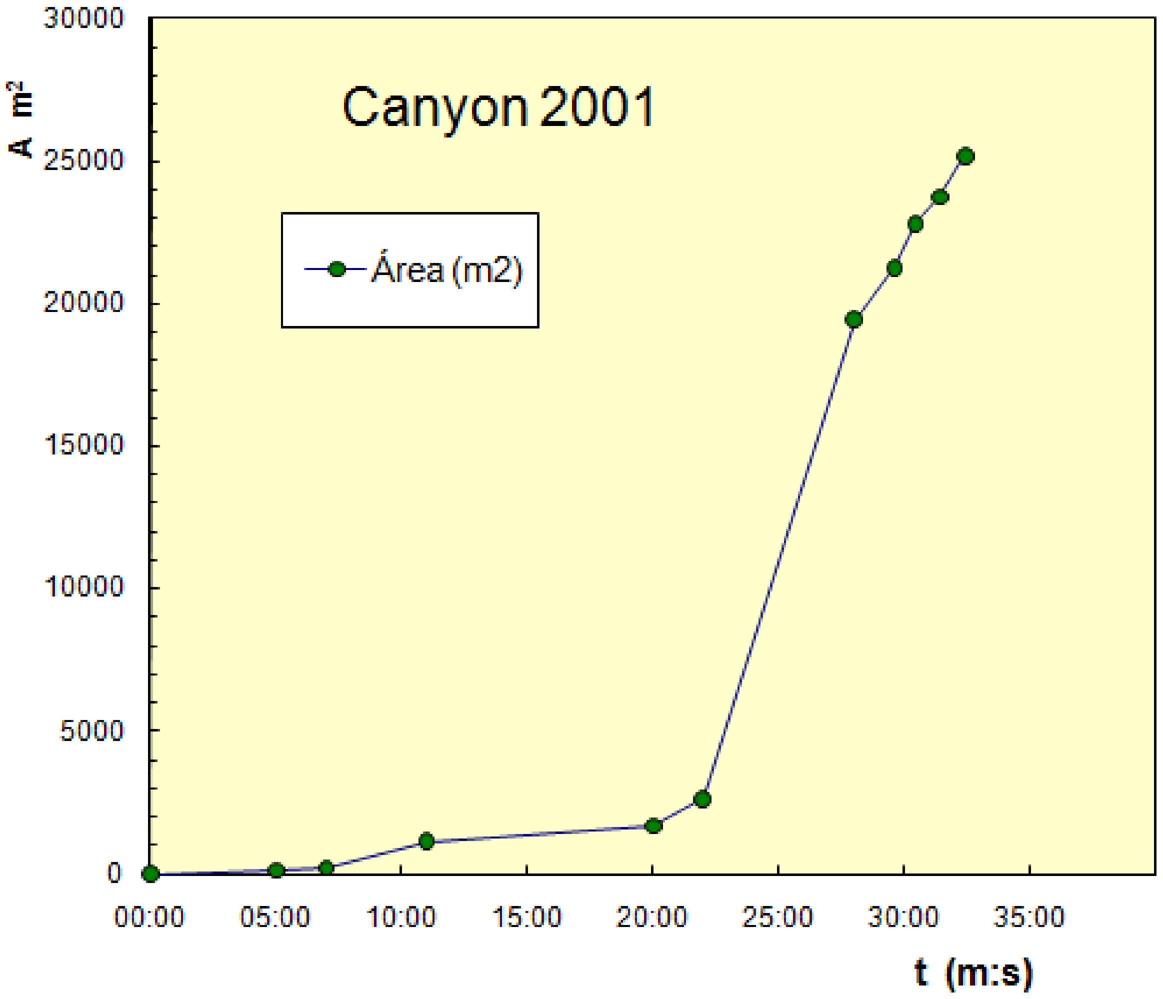
α=20º
δ=30º

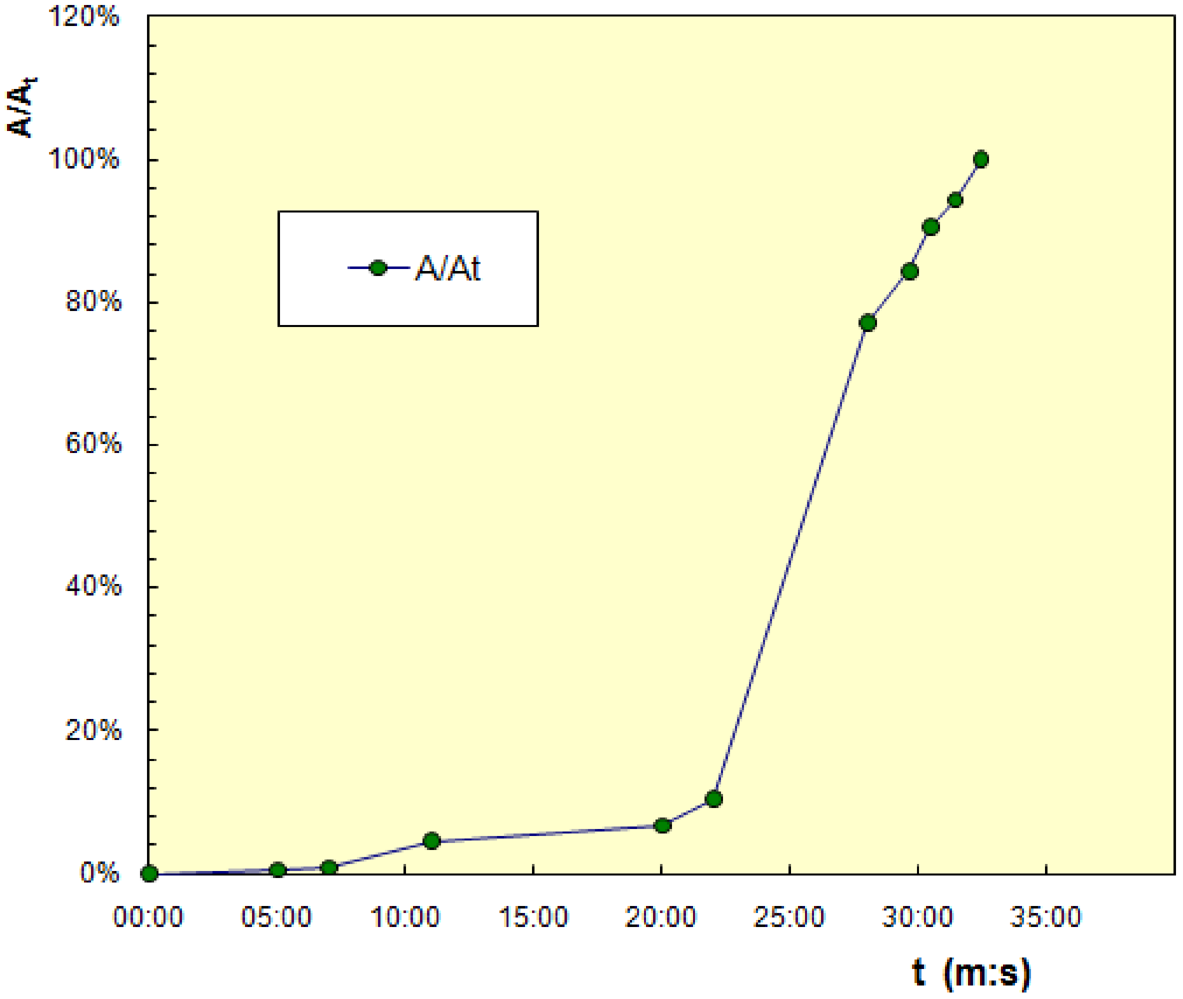


α=30º
δ=30º

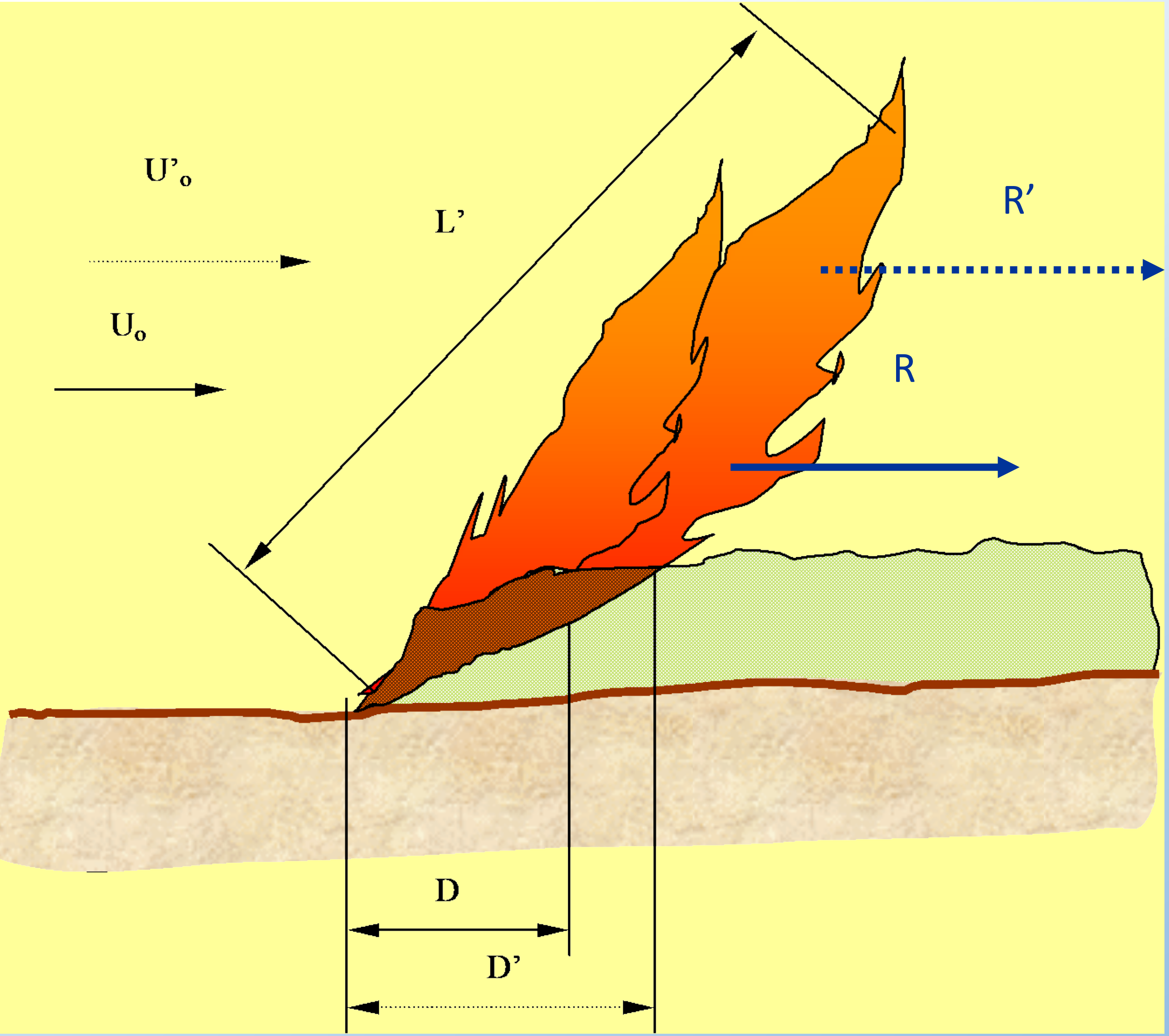


Field experiment 2001


Canyon 2001
Área (m2)
A m2
30000
25000
20000
15000
10000
5000
0
00:00
05:00
10:00
15:00
20:00
25:00
30:00
35:00
t (m:s)


A/At
A/At
120%
100%
80%
60%
40%
20%
0%
00:00
05:00
10:00
15:00
20:00
25:00
30:00
35:00
t (m:s)

Horizontal fuelbed with wind



$$dR' = a_1 . b_1 . U^{b_1 - 1} dU$$

$$dU = a_2 . b_1 . R'^{b_2} dt$$

$$\frac{dR'}{dt} = a_1 . \frac{1}{b_1} . b_2 . (R' - 1)^{1 - \frac{1}{b}} R'^{b_2}$$

Differential equation of the eruptive fire (non-dimensional form):

$$\frac{dR'}{dt'} = {a'_1}^{\frac{1}{b_1}} a'_2 b_1 (R' - 1)^{1-\frac{1}{b_1}} R'^{b_2}$$

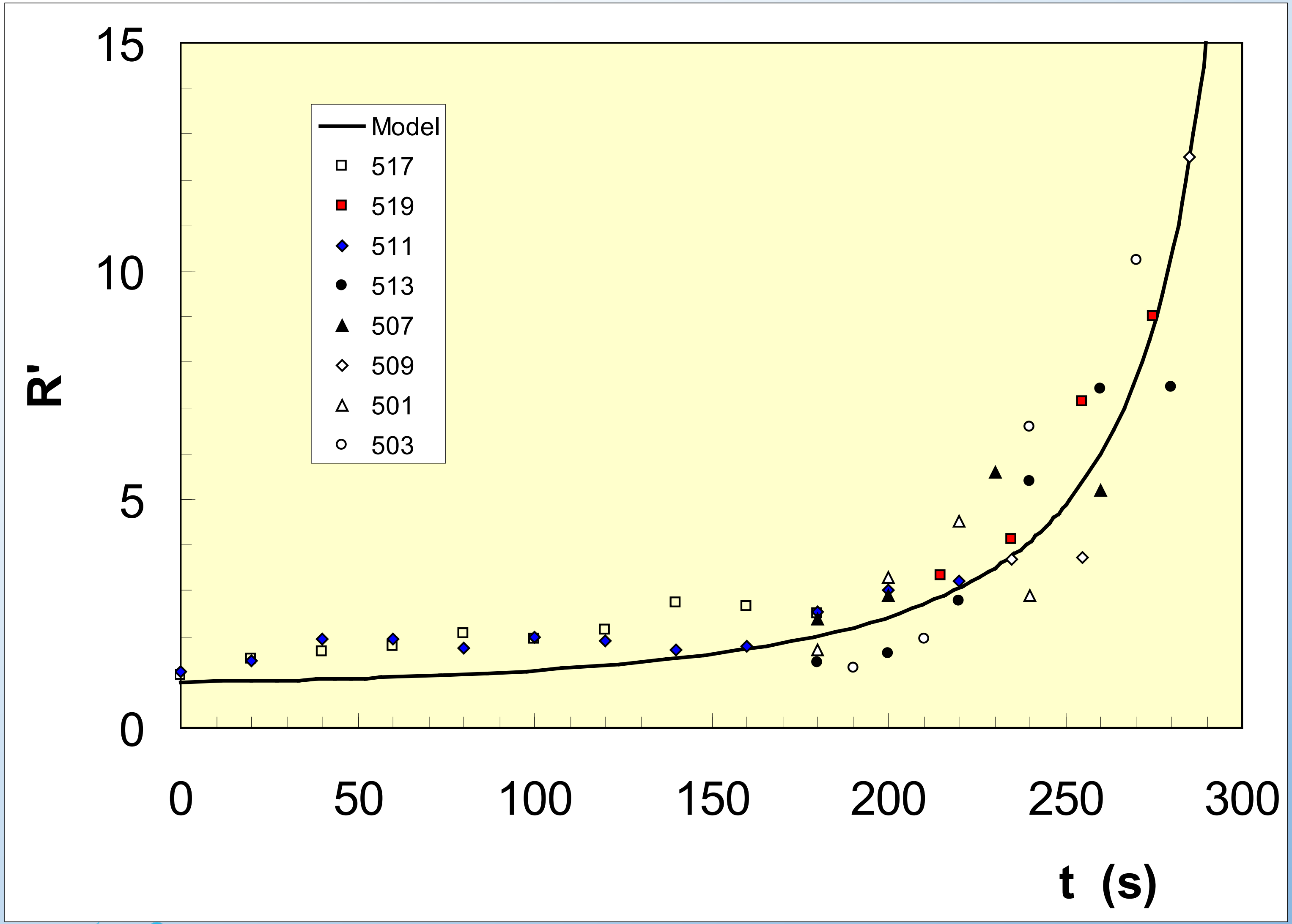
$$R' = \frac{R}{R_o}$$

$$t' = \frac{t}{t_o}$$

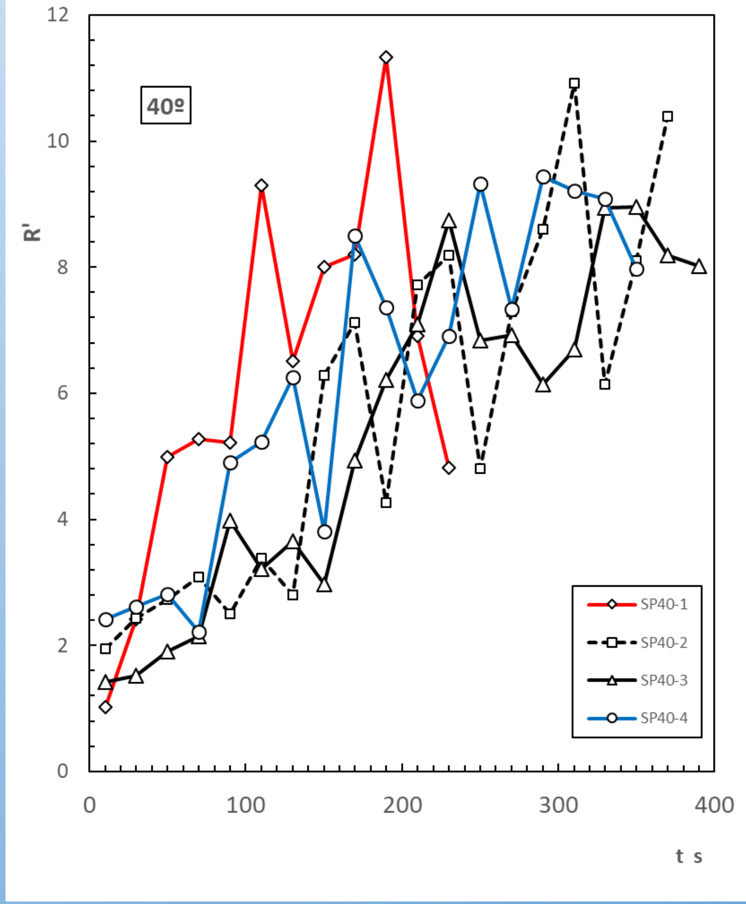
R_o is the basic ROS (No Slope and No wind)

t_o is the residence time of the flame in the fuel

Canyon



40º Slope



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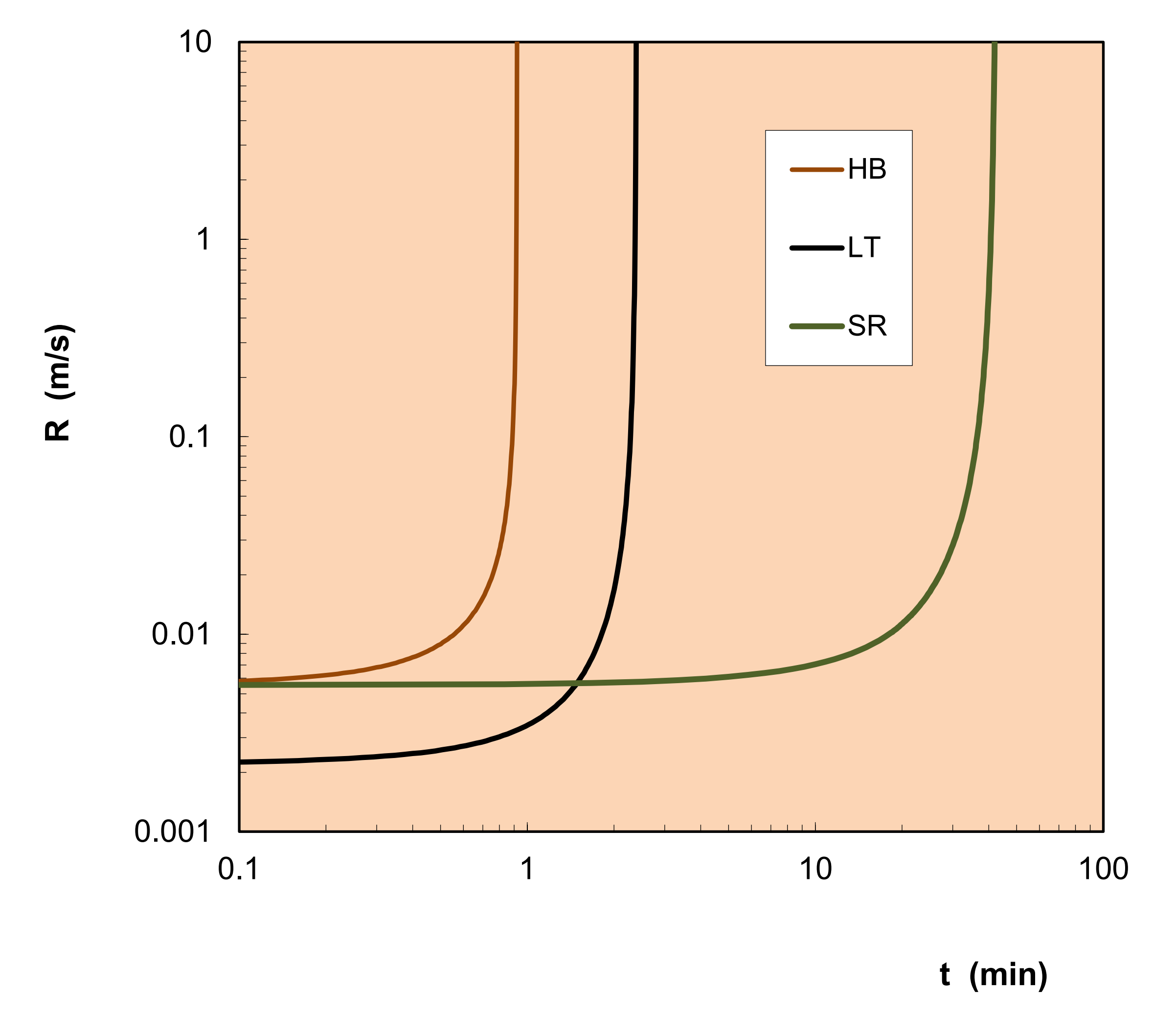
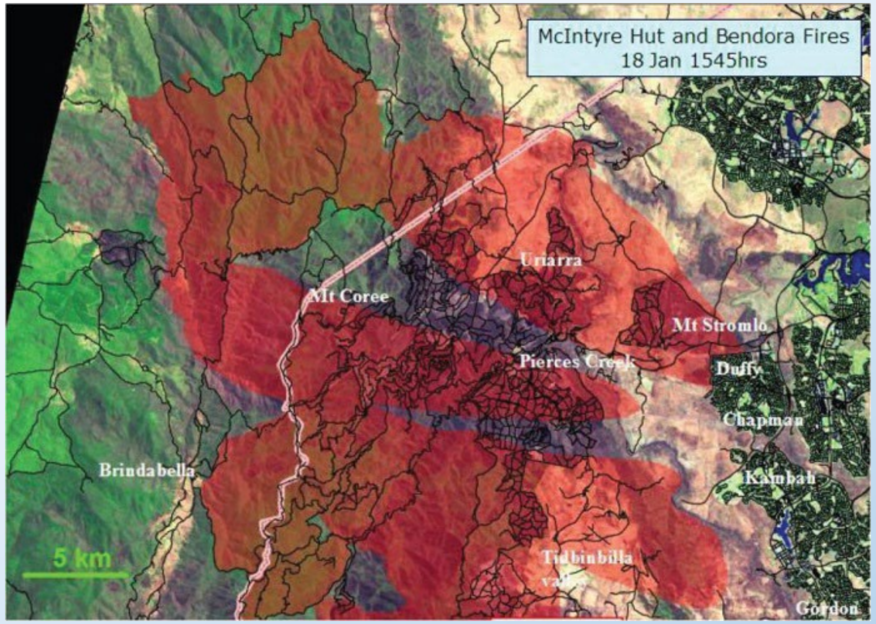


HB	Herbaceous
LT	Litter
SR	Shrub

Viegas DX, 2006. Parametric Study of an Eruptive Fire Behaviour Model. Int. J. Wildland Fire. 15(2):169-177.

Merging of two oblique fronts



Canberra 2003

Teste laboratorial

Teste CF-08

θ = 30º

α = 30º

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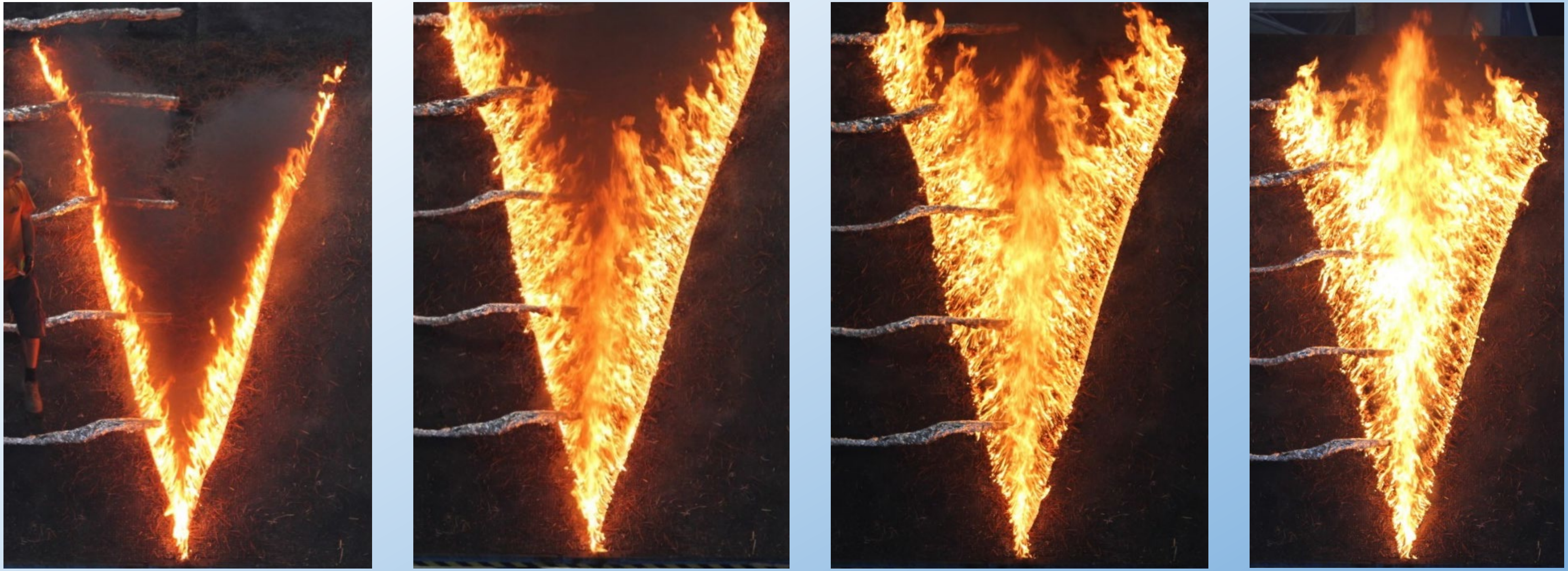
Laboratory simulation of two merging fronts



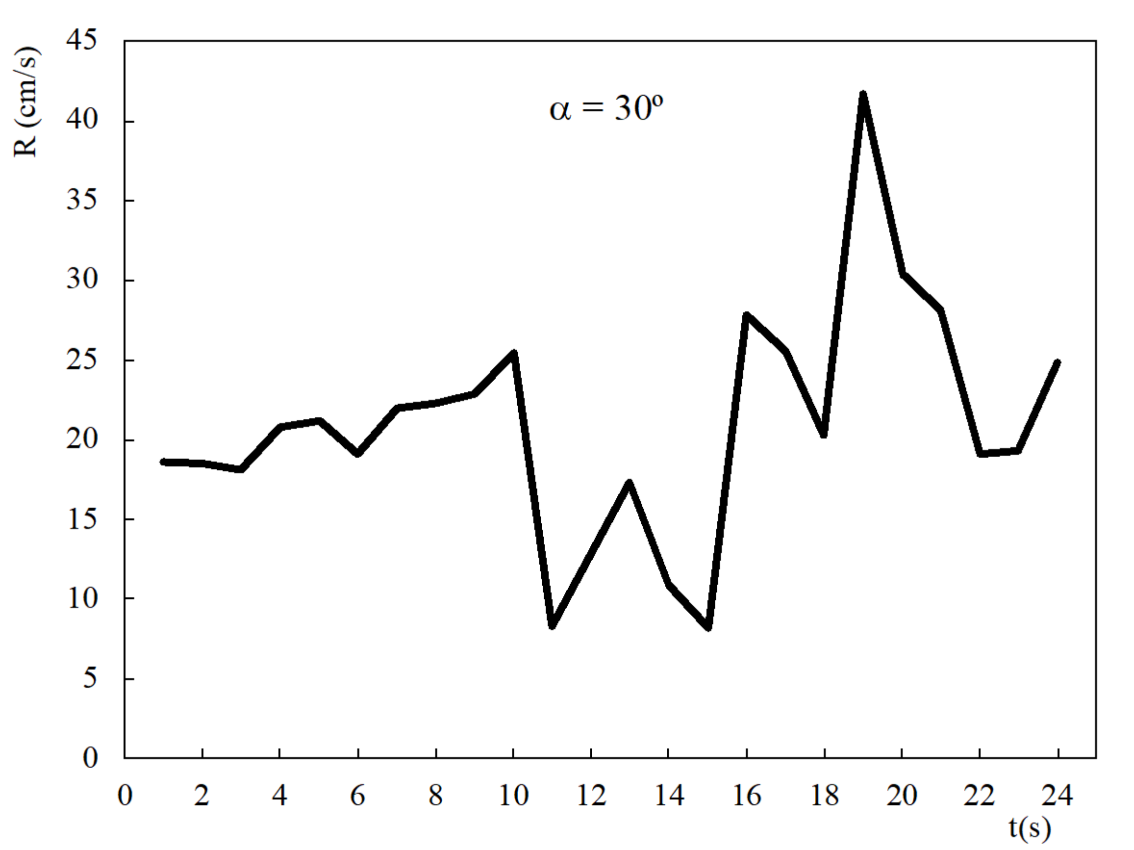
$\Delta t = 3$ s

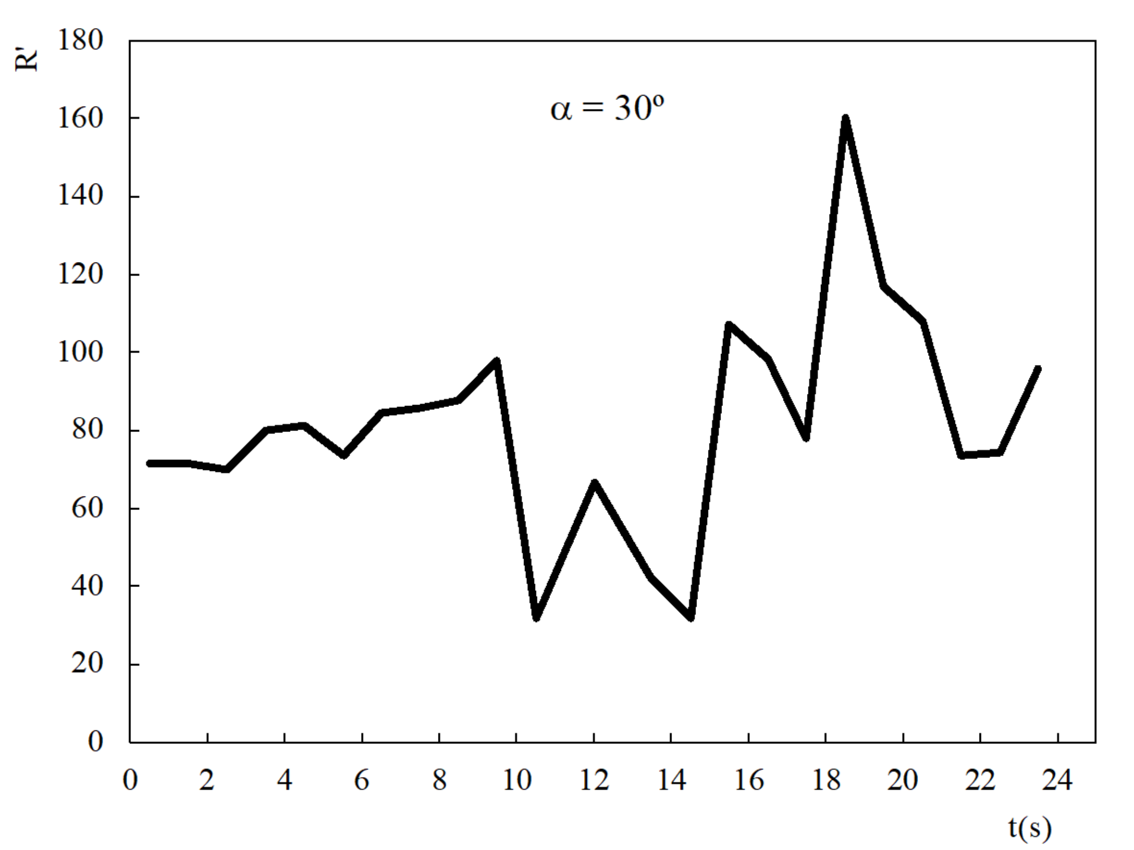
Viegas *et al.*, 2012. Study of the Jump Fire. Part 1. Int. J. Wildland Fire. 21:843-856.

Raposo *et al.*, 2018. Analysis of the physical processes associated with junction fires at laboratory and field scales. Int. J. Wildland Fire. 27:52-68.

Test with 30º slope (*Pinus pinaster* needles)

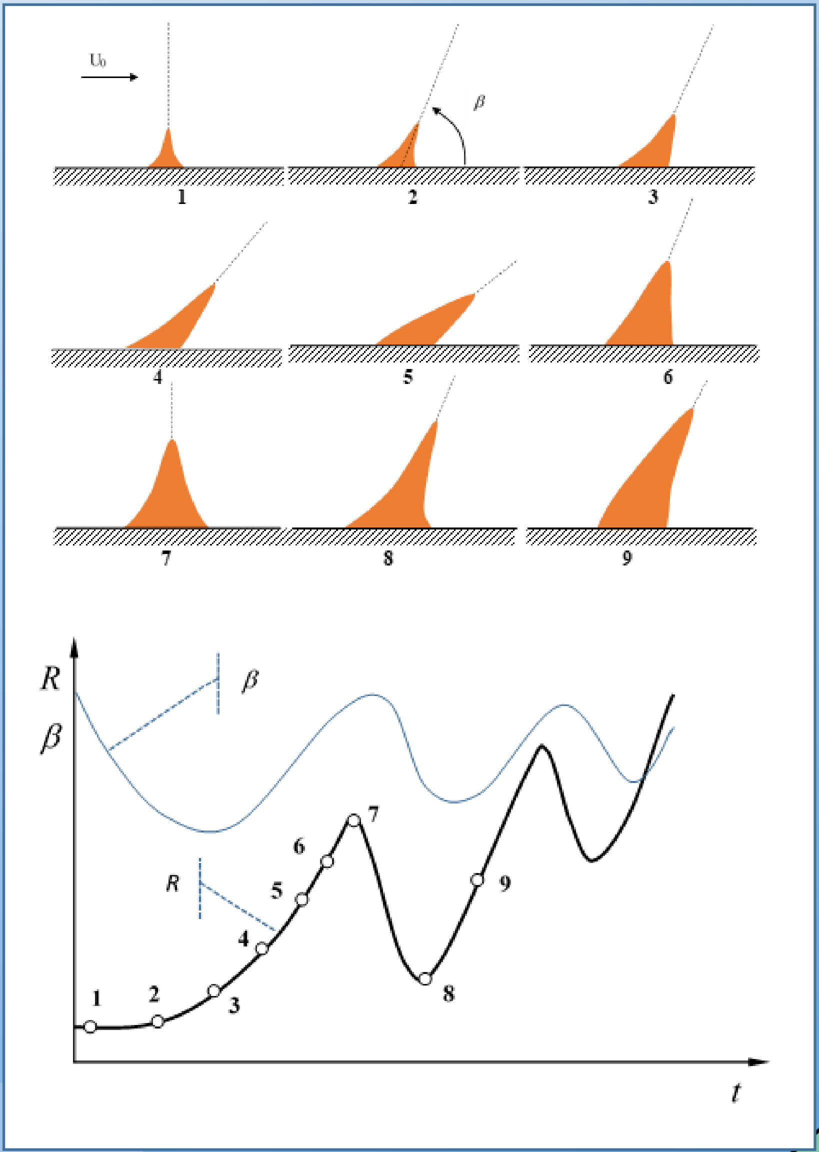
ROS of the head fire



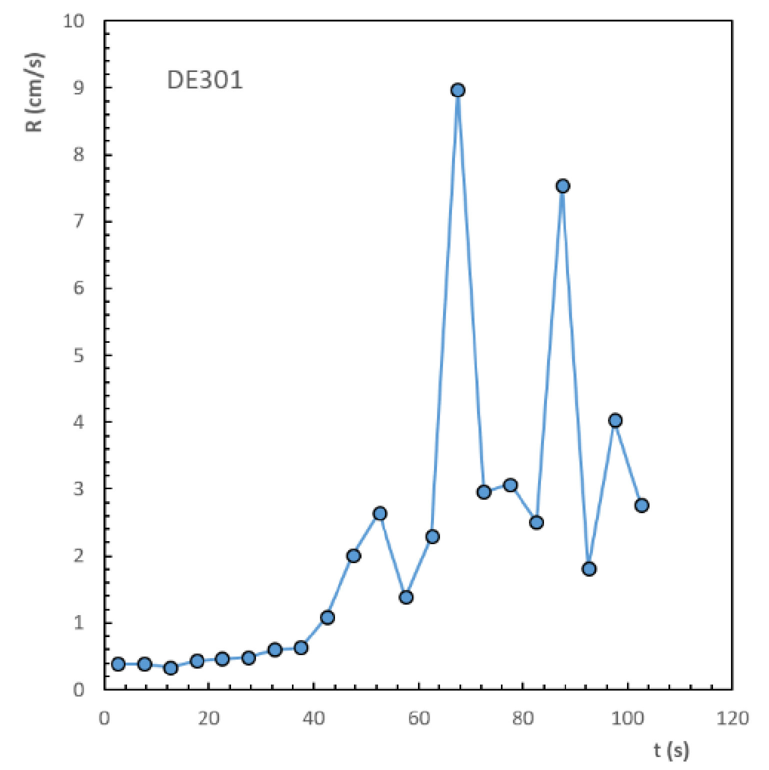


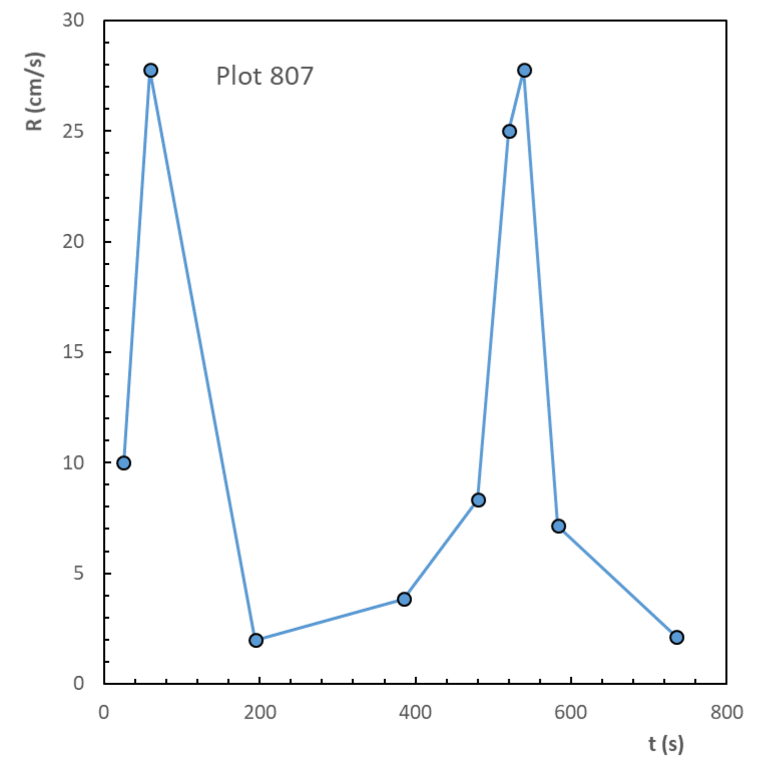
3. Intermittent or oscillatory fire behaviour

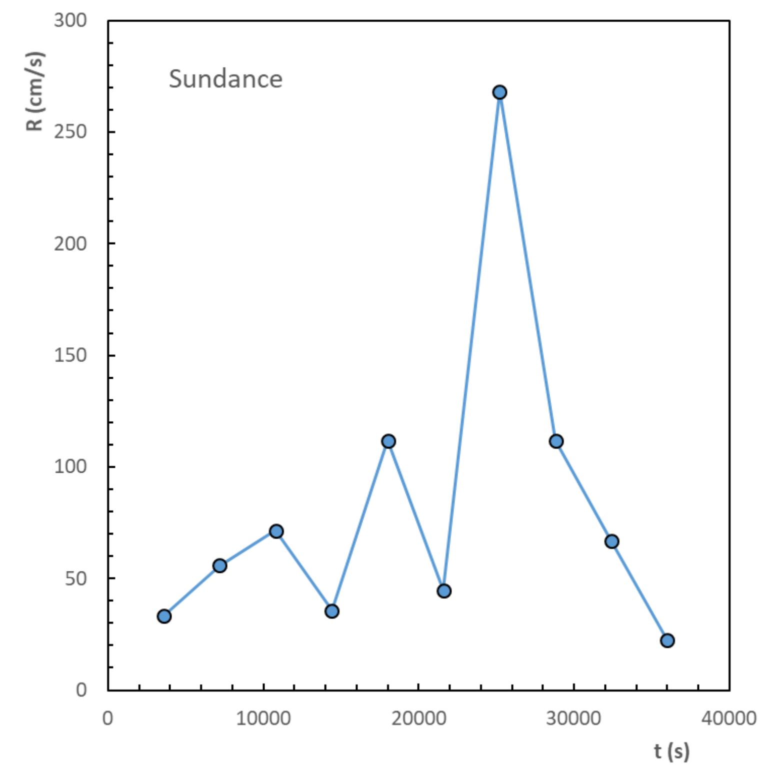
- The behaviour of a fire is oscillatory and intermittent, in the sense that its ROS may increase but then the convective flow induced by the fire counteracts the acceleration tendency and decreases the ROS value; the fire will undergo another cycle of ROS increase and decrease as it is observed in various carefully documented laboratory and field experiments and in real fires as well.



Viegas DX, et al., 2021. On the non-monotonic Behavior of Fire Spread, Int. J. Wildland Fire. https://doi.org/10.1071/WF21016.



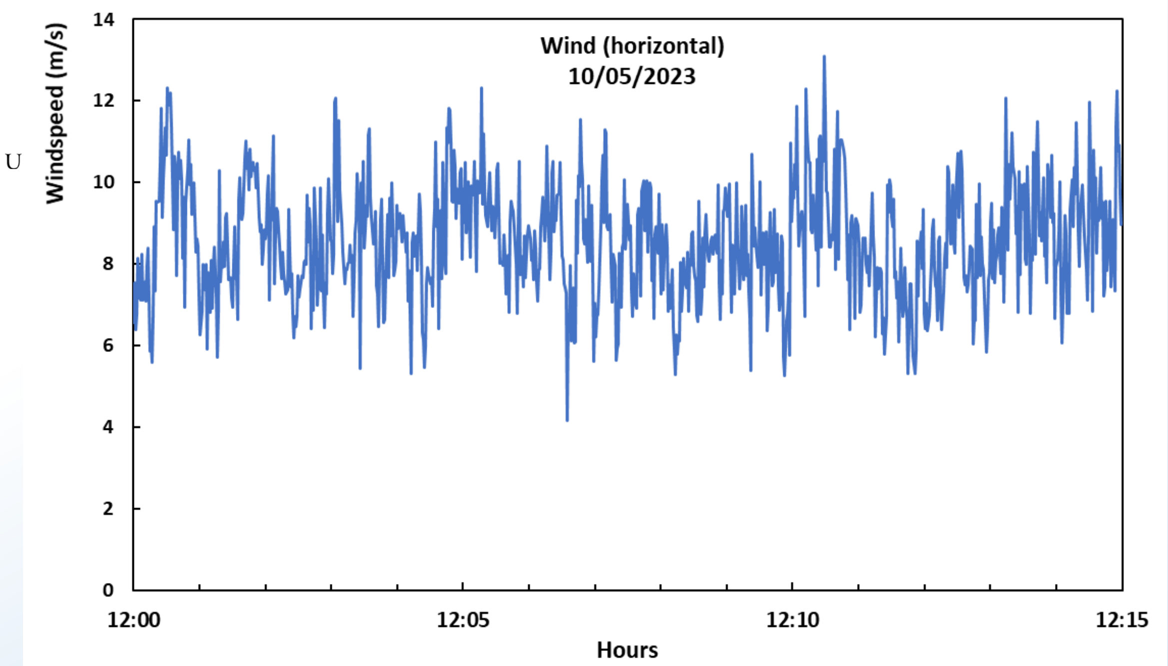




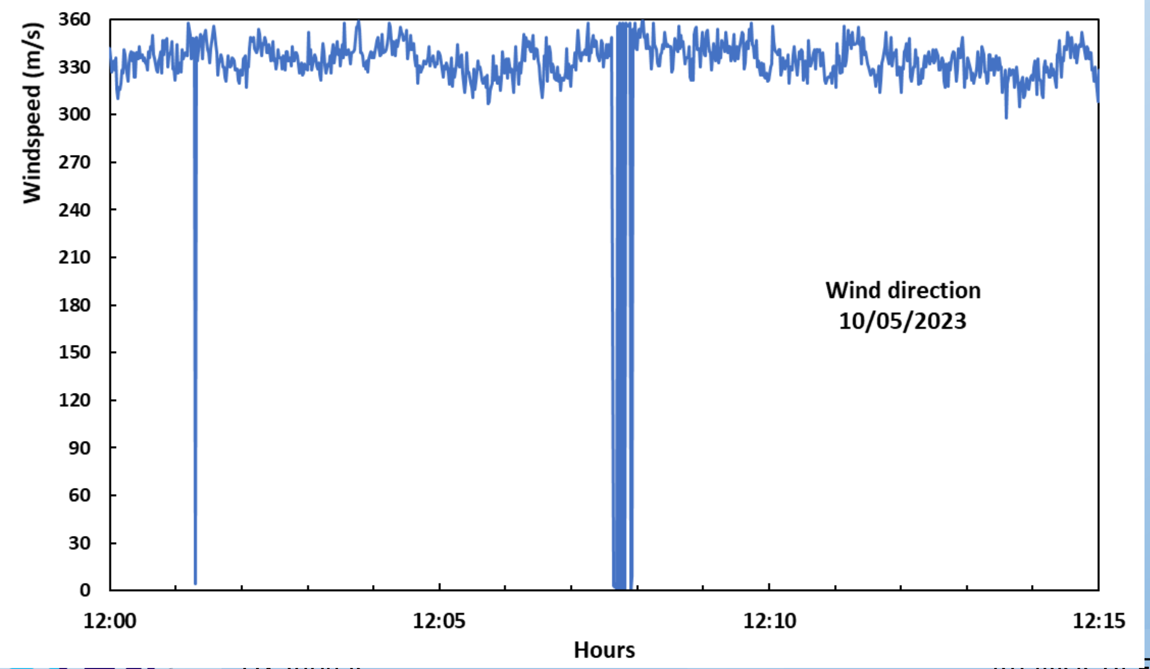
Lab Test | Field experiment | Sundance Fire

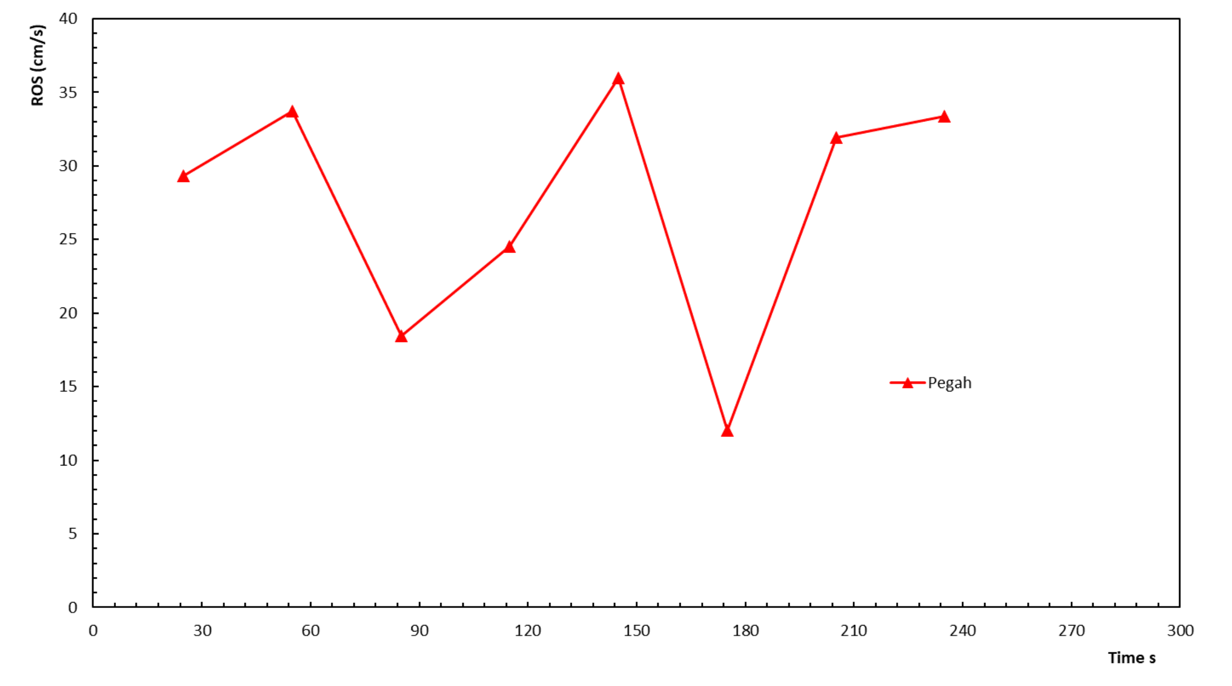
Viegas DX, et al., 2022. On the intermittent nature of forest fire spread- Part 2, Int. J. Wildland Fire. https://doi.org/10.1071/WF21098.

DX Viegas


U
Windspeed (m/s)
Wind (horizontal)
10/05/2023
14
12
10
8
6
4
2
0
12:00
12:05
12:10
12:15
Hours


Gestosa
10 May 2023


Windspeed (m/s)
360
330
300
270
240
210
180
150
120
90
60
30
0
Wind direction
10/05/2023
12:00
12:05
12:10
12:15
Hours


ROS (cm/s)
40
35
30
25
20
15
10
5
0
Pegah
0
30
60
90
120
150
180
210
240
270
300
Time s

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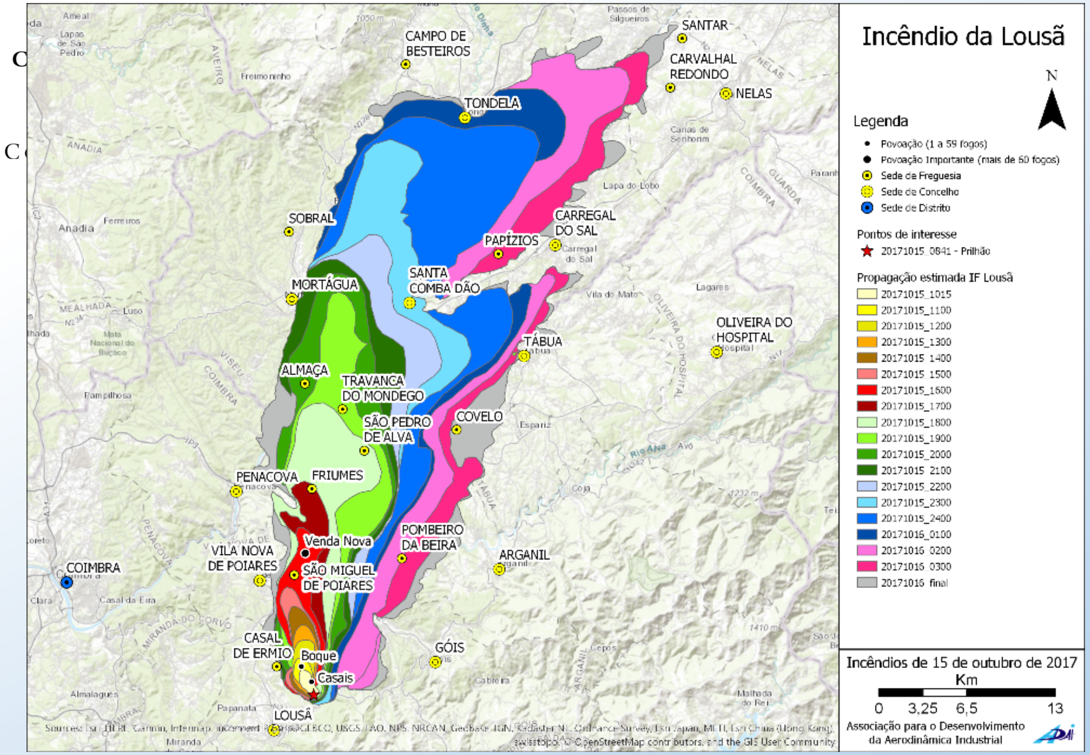
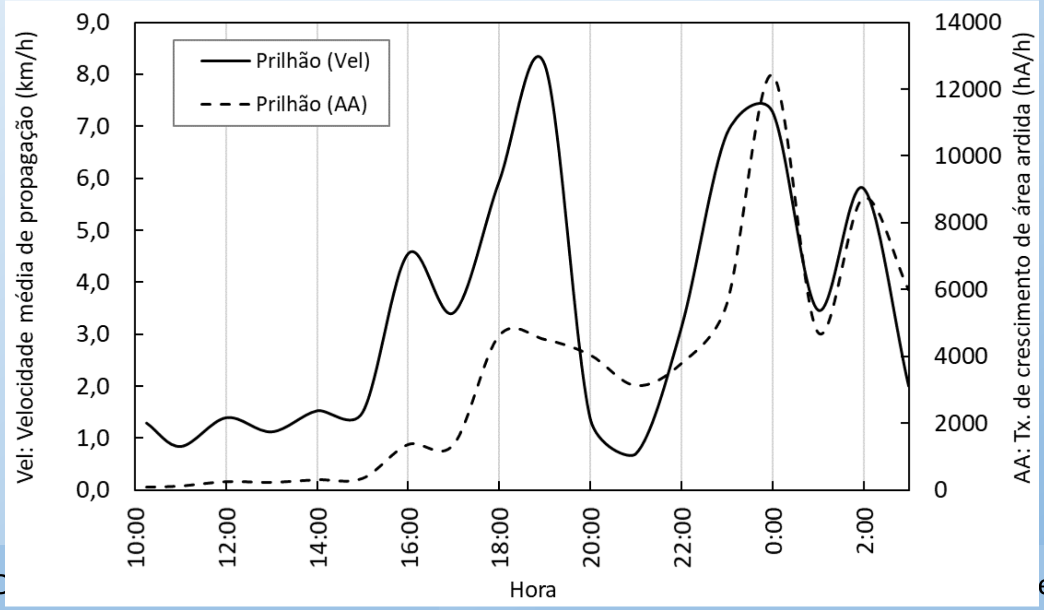
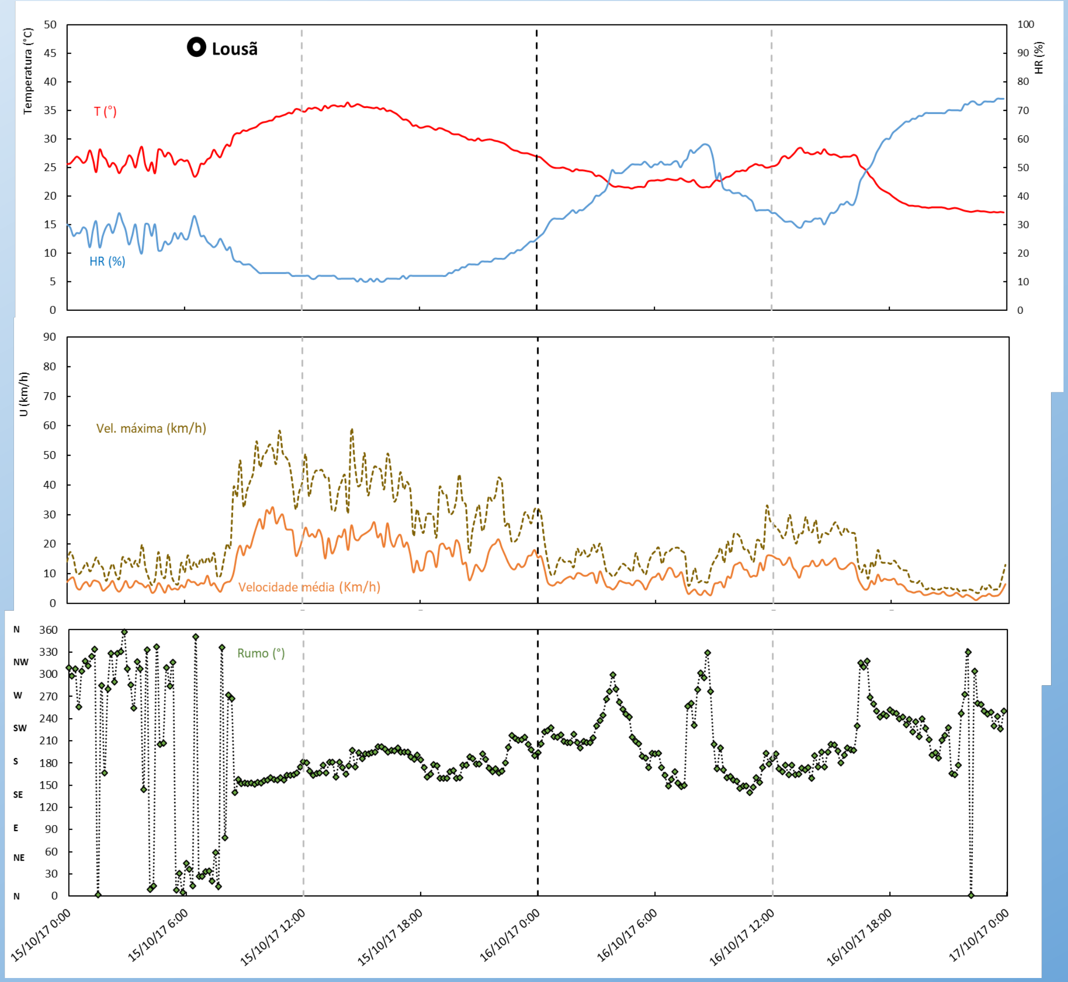
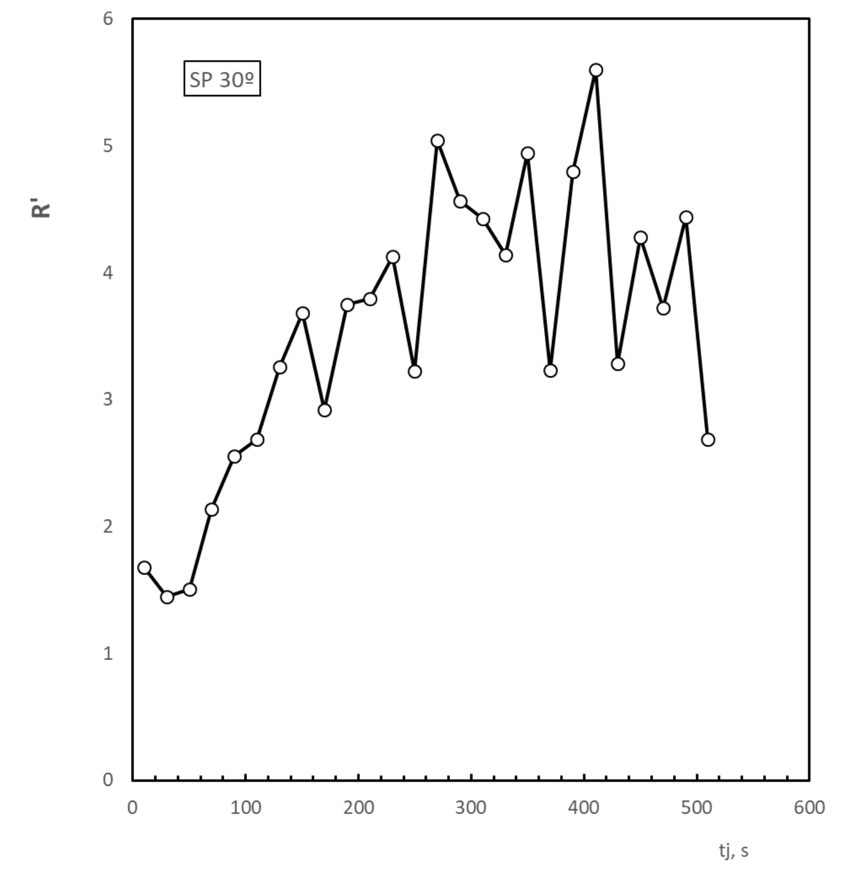
Fire of Lousã, 15 October 2017
53kHa, 23 victims

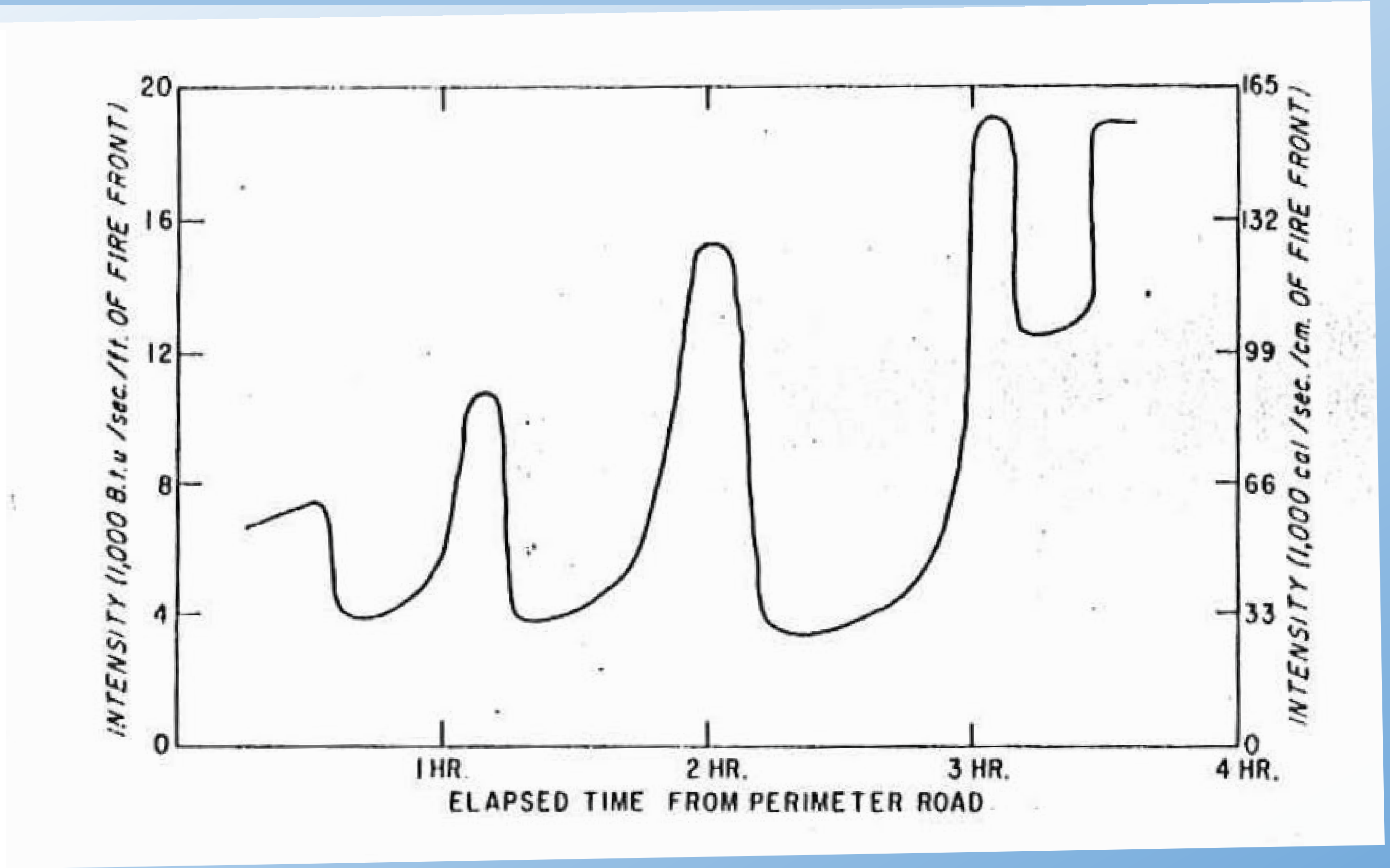






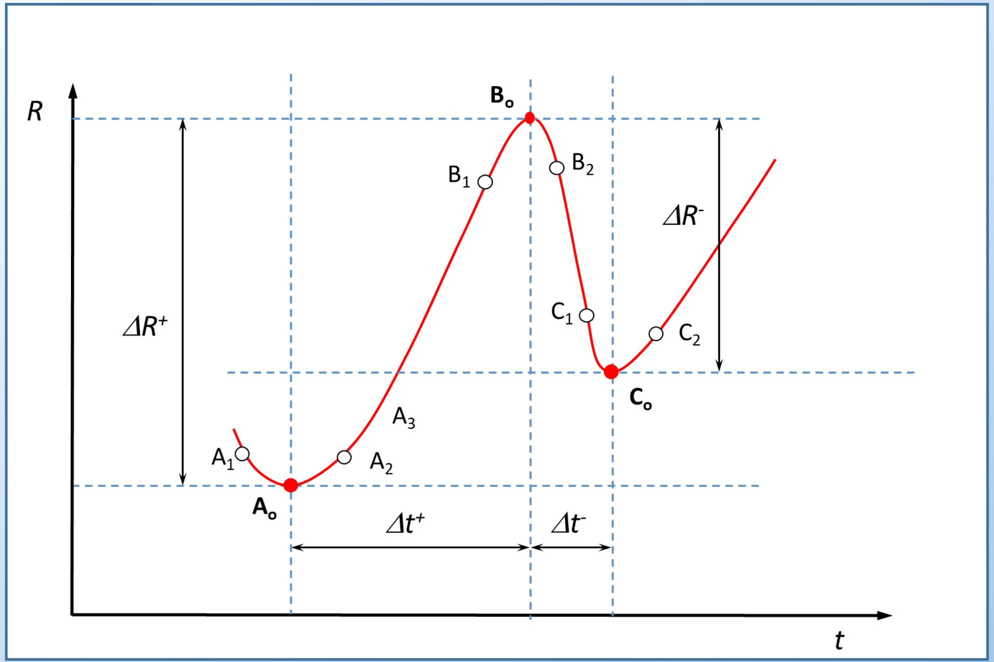
Oscillatory behaviour of fire





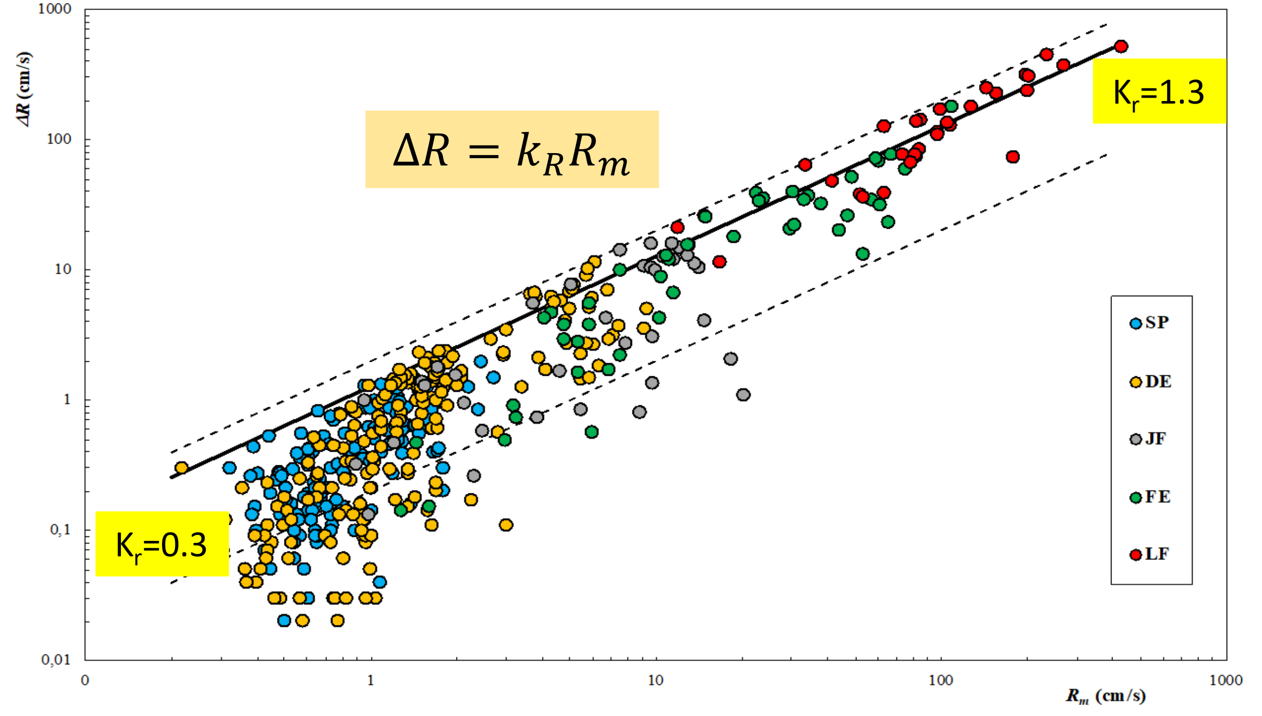
Lab. experiment (Slope 30º) Bomb Range Fire

R(t) during fire evolution in two semi-periods



$$R_m = \frac{R_1 + R_2}{2}$$

Amplitude of fluctuations of the ROS as a function of the average value of R_m for all cases



$$\Delta R = k_R R_m$$

Laboratory Field Real Fires

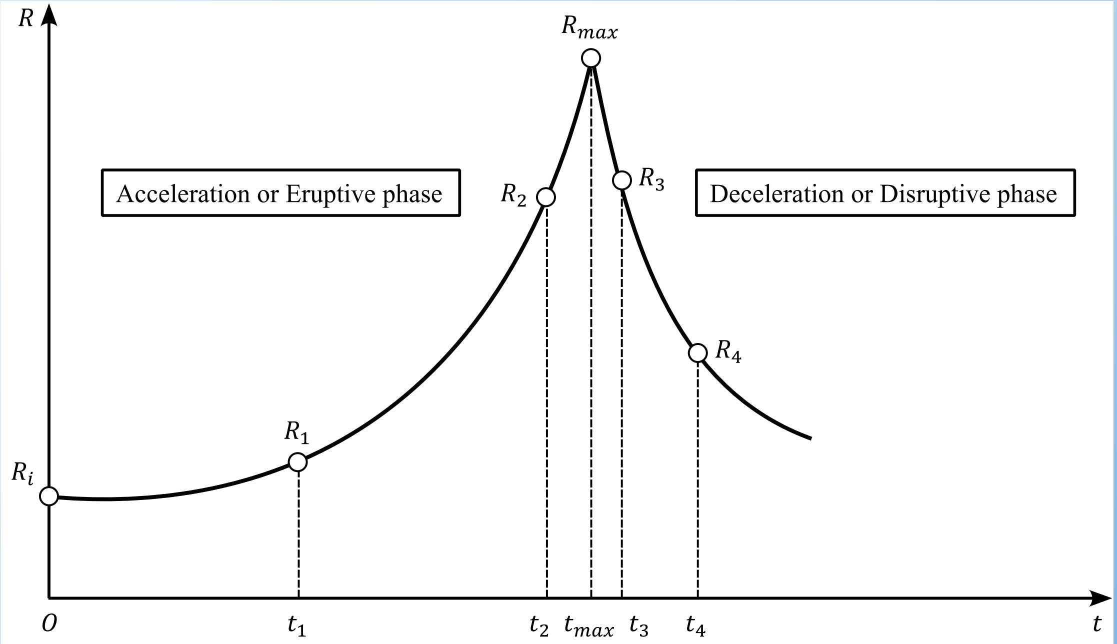
- The concepts of “convective fire”, “topographic fire” or “wind induced fire” as “types of fires” are erroneous, as wind and topography may be always present as well as convection.

(Mount Carmel, 2010)

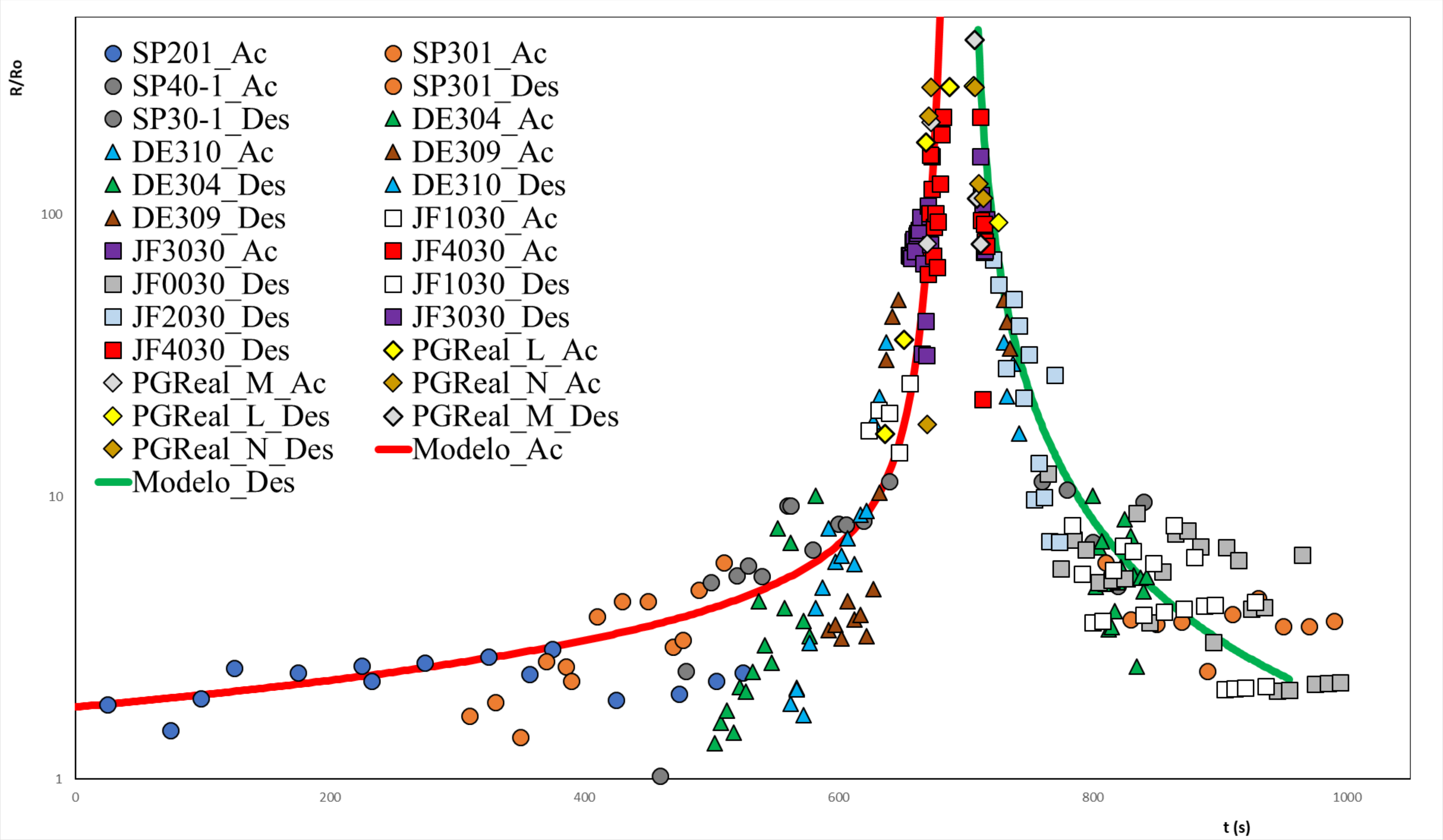
Acceleration and Deceleration of the Head Fire

$$\frac{dR'}{dt} = a_1^{\frac{1}{b_1}} b_1 a_2 \left(\frac{R'-1}{a_1}\right)^{1-\frac{1}{b_1}} R'^{b_2}$$

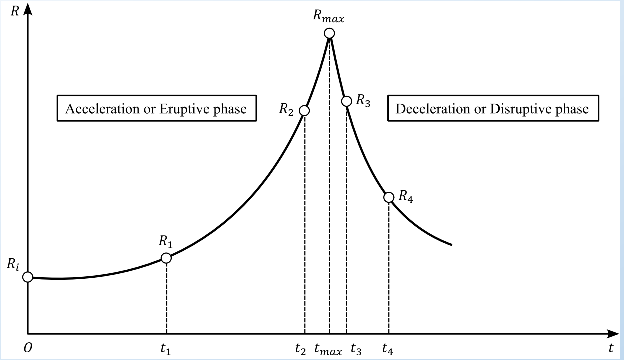
$$\frac{dR'}{dt'} = -a'_1{}^{\frac{1}{b_1}} b_1 a'_3 (R'-1)^{1-\frac{1}{b_1}} R'^{b_3}$$

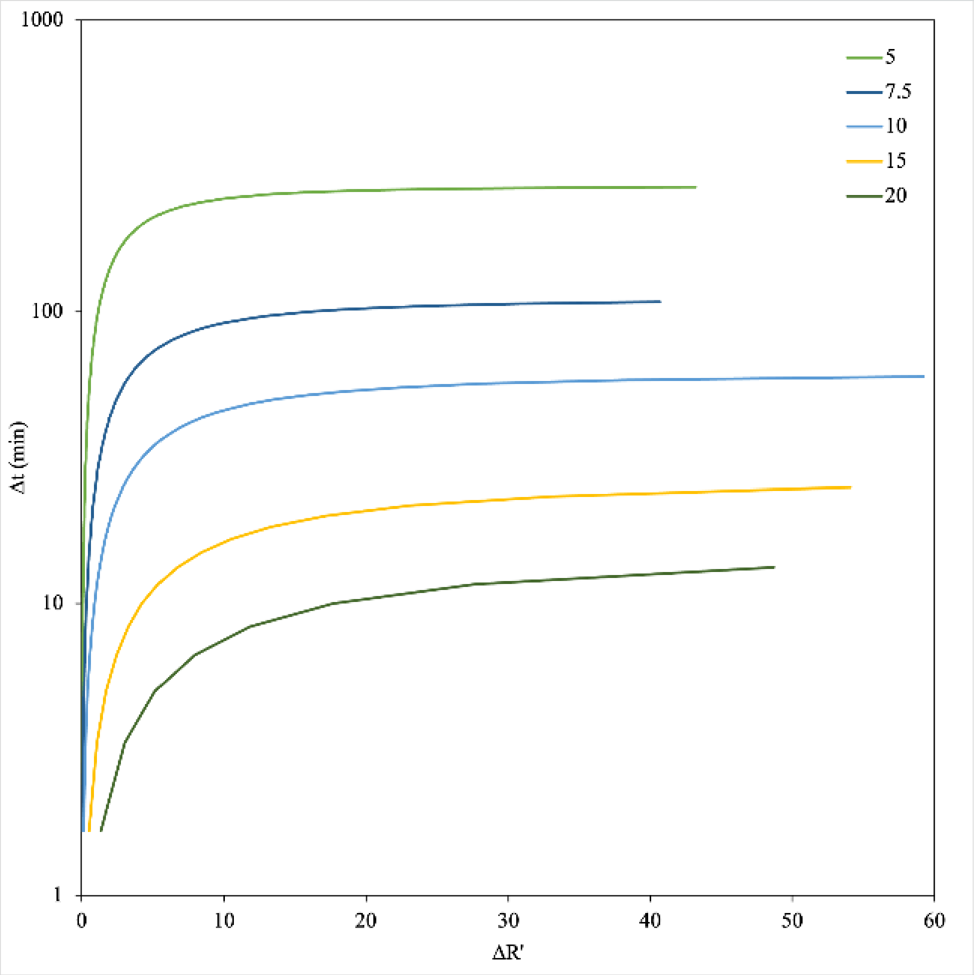


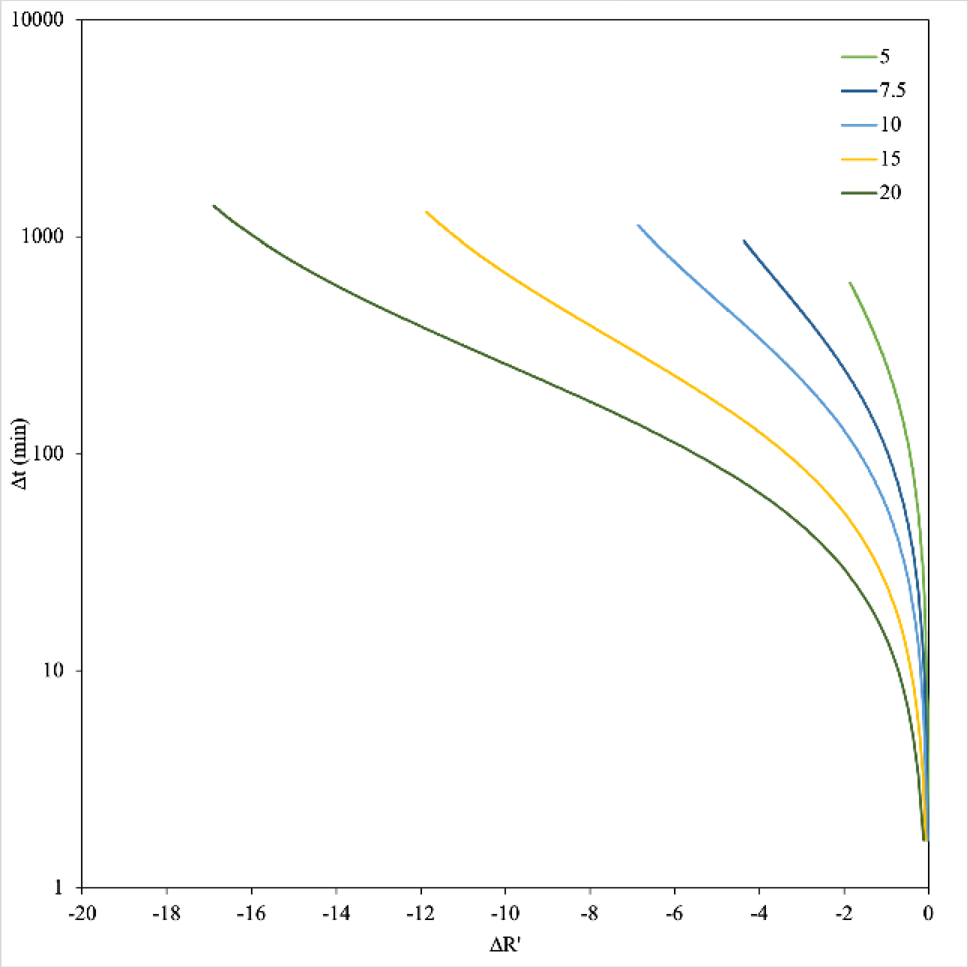
Mathematical model of acceleration and deceleration



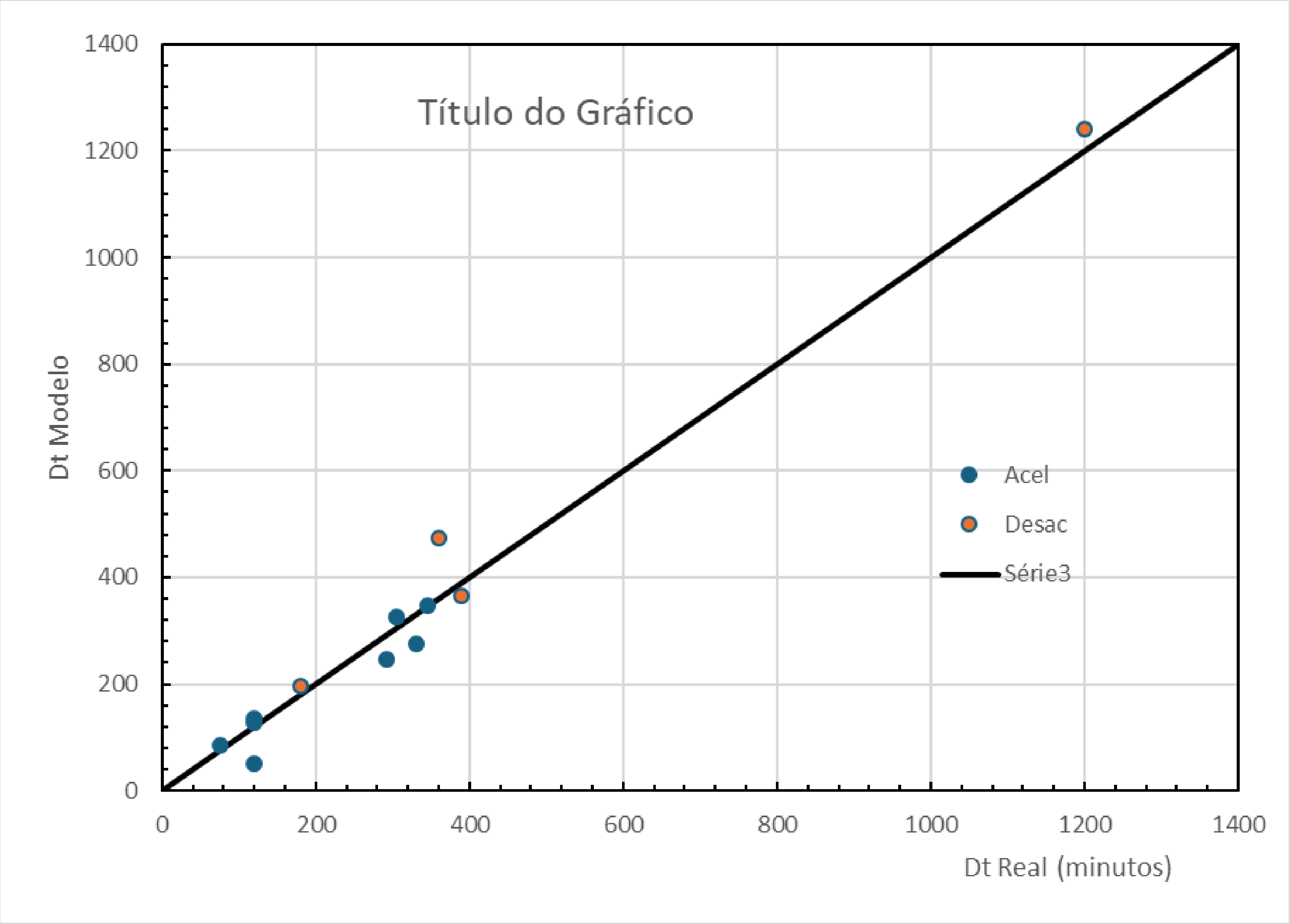
Time delay required for a given variation of ROS







Comparison between model prediction and observations



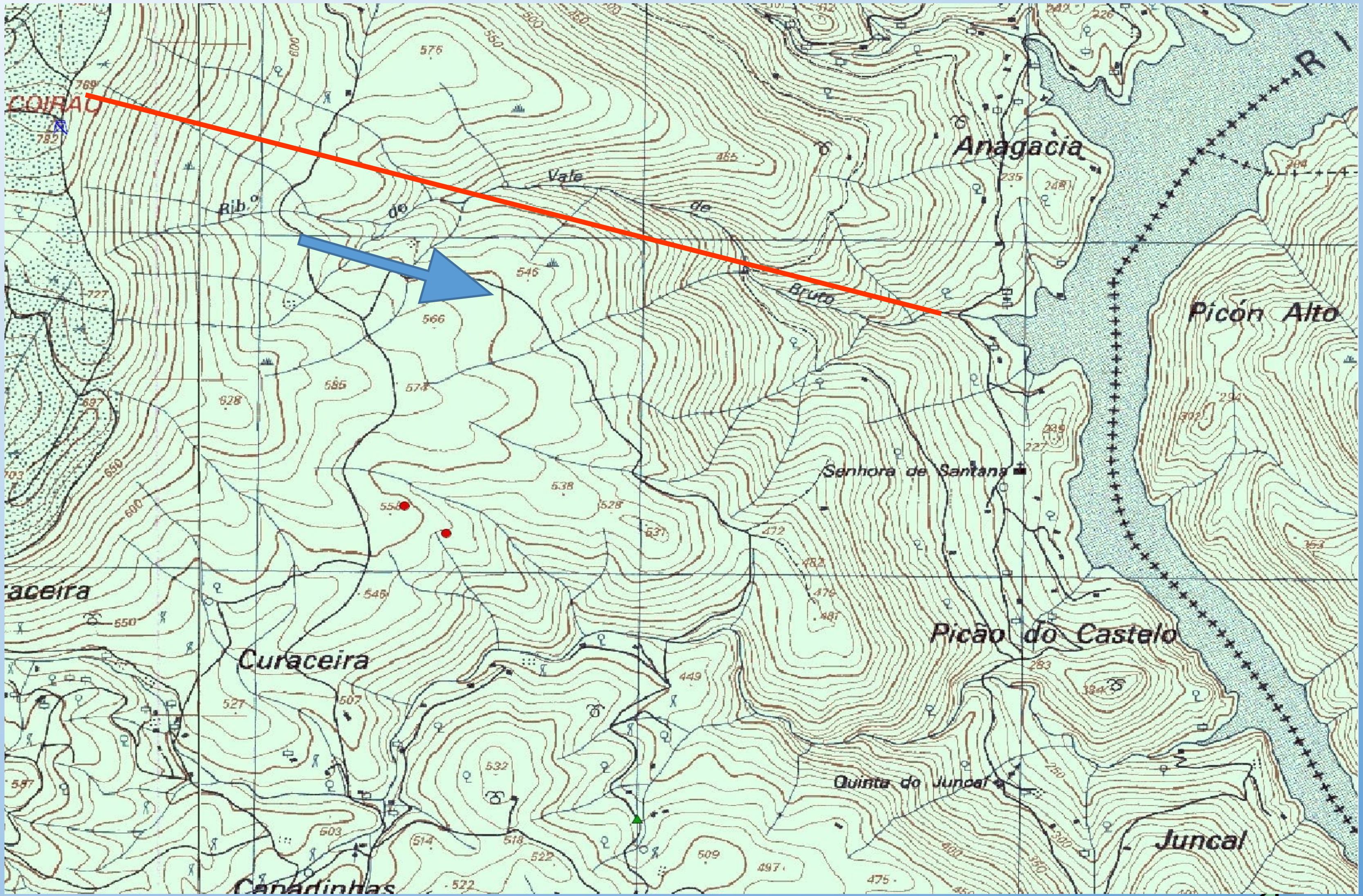
Case study

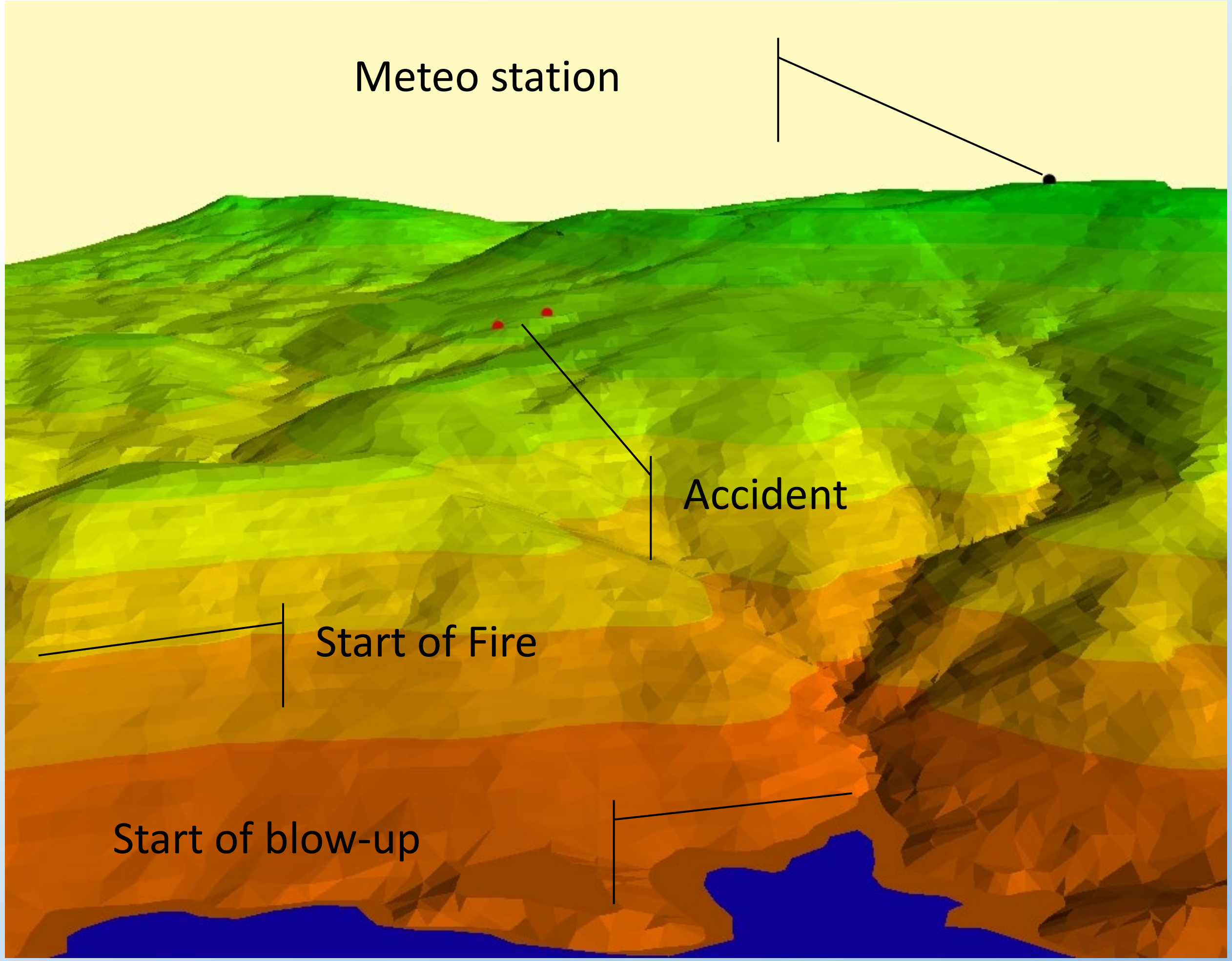
- We could present dozens of cases of fire eruption in canyons, most of them associated to accidents with multiple fatalities.
- I will mention the case of Freixo de Espada à Cinta that occurred in Portugal on the 5th of August of 2005, causing the death of two persons.

Topographic Map

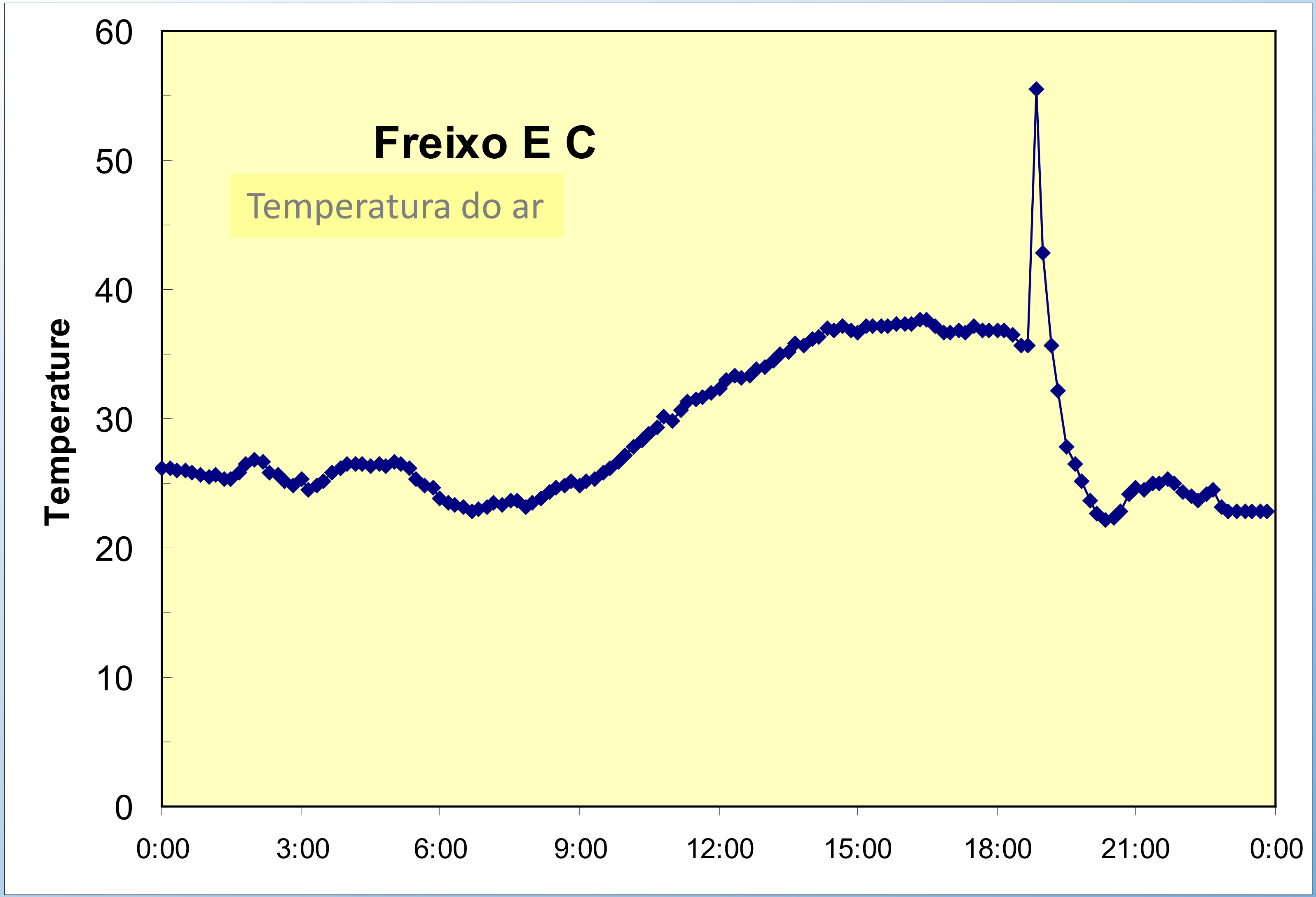
Accident of Freixo de Espada à Cinta

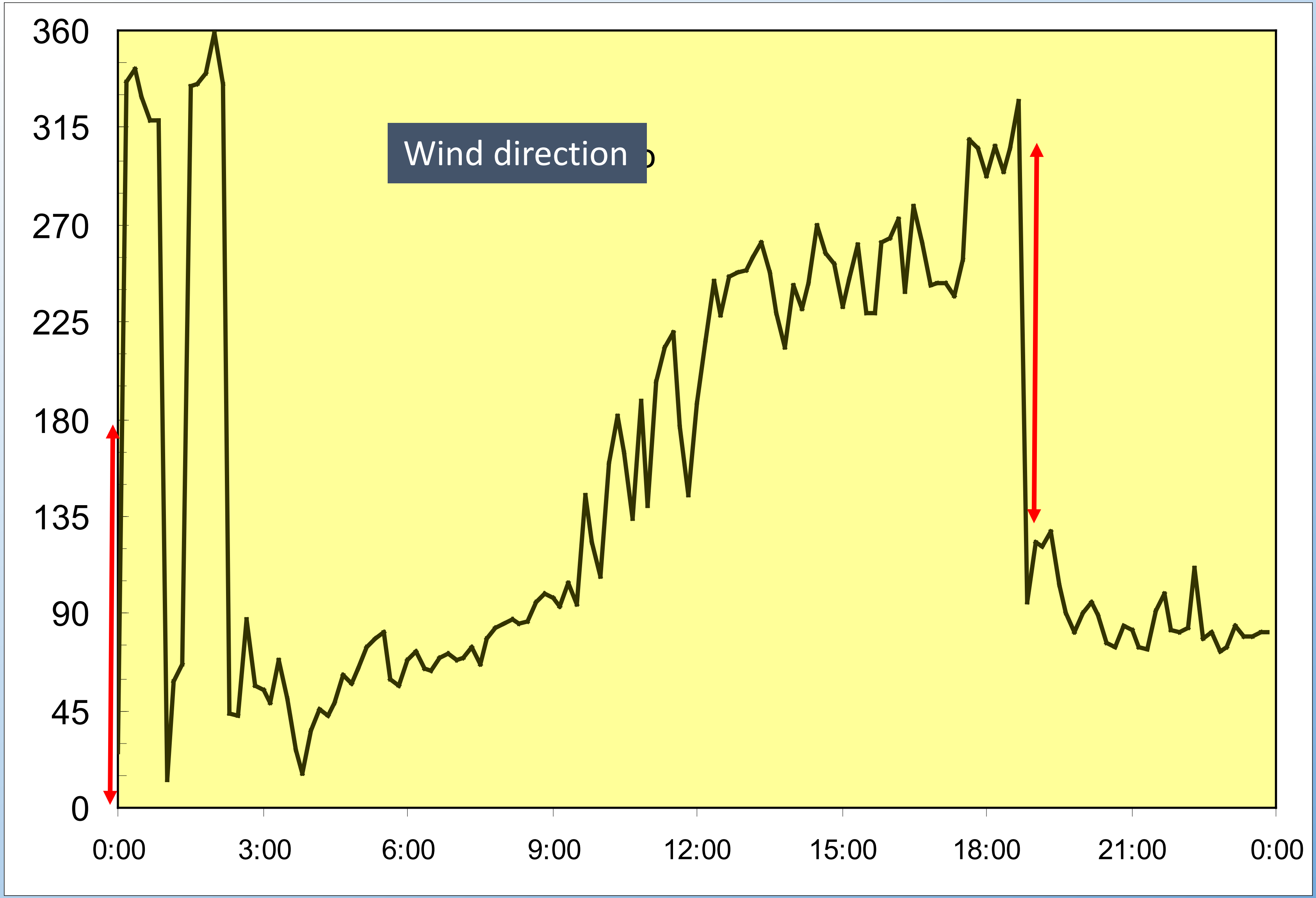
- 5 August 2003
- 2 victims

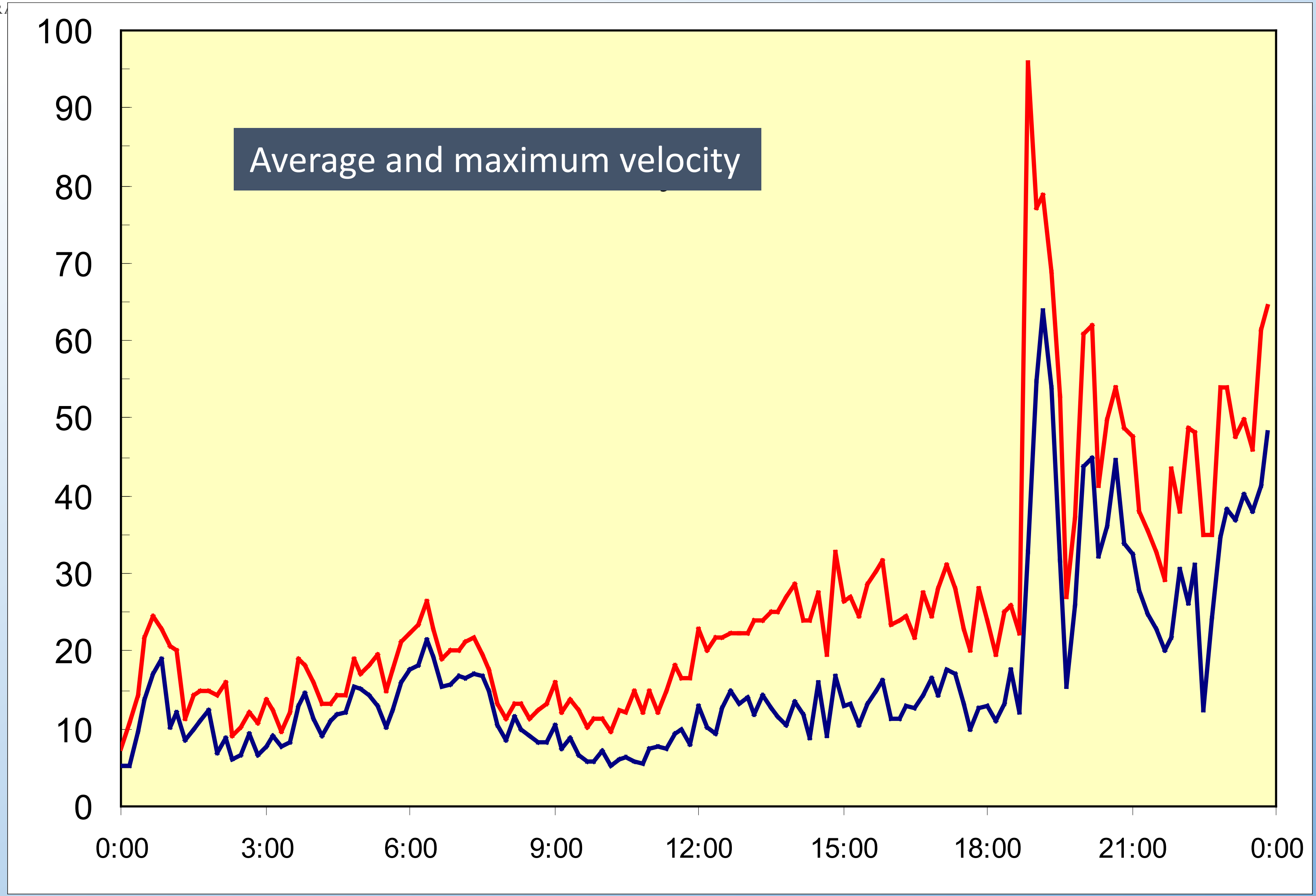



Meteo station
Accident
Start of Fire
Start of blow-up

Meteo Station


Freixo E C
Temperatura do ar
Temperature
60
50
40
30
20
10
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00


Wind direction
360
315
270
225
180
135
90
45
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00


Average and maximum velocity
100
90
80
70
60
50
40
30
20
10
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

The fire of Pedrógão Grande

16 de junho de 2017

Origin of the fires in Escalos Fundeiros and Regadas

Interação com a trovoada

18h00

18.15H

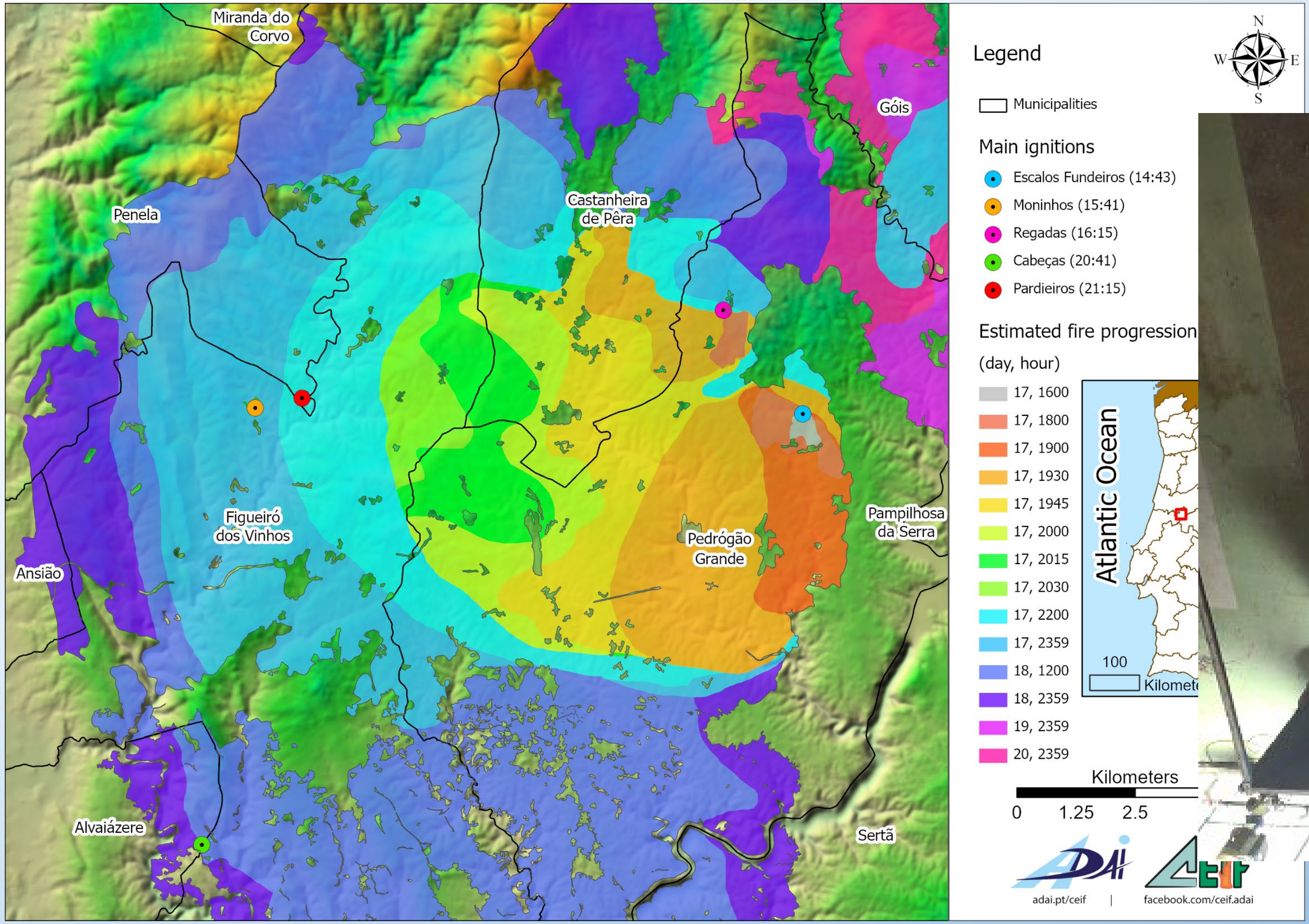
19h35

19h40

19h45

20h00

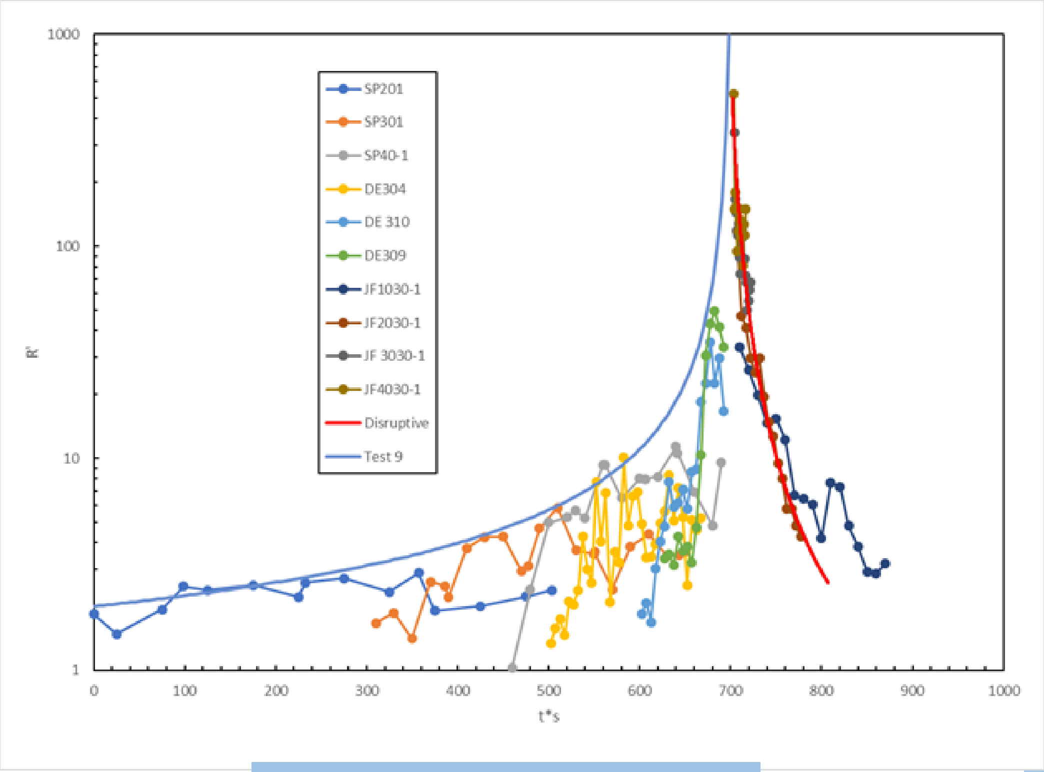
The case of Pedrógão Grande Fire (Portugal, June 2017, 66 fatalities)



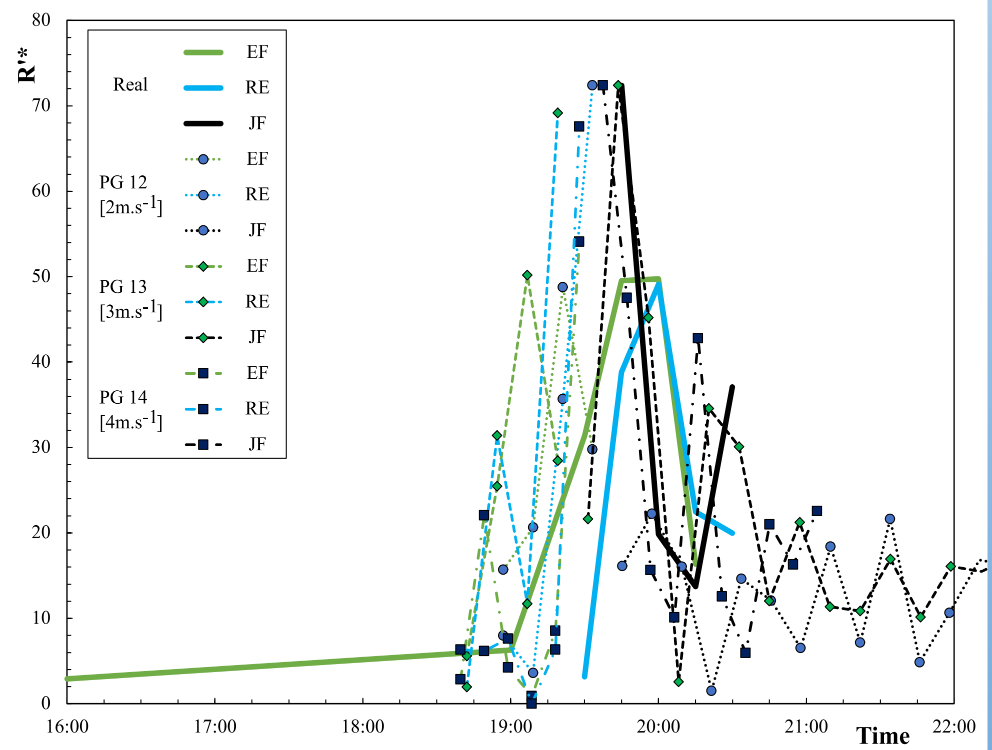
Acceleration and deceleration of the head fire

Joint analysis of the acceleration and the deceleration of the fire

$$\frac{dR'}{dt'} = a'_1{}^{\frac{1}{b_1}} b_1 a'_2 (R' - 1)^{1-\frac{1}{b_1}} R'^{b_2}$$



Laboratory experiments



Fire of Pedrógão Grande

Analysis of Extreme Fire Behaviour


S.JOÃO

4 - Conclusion

- The study of fire behaviour is central to understand all processes associated to wildfires.
- The behaviour of a fire is dynamic due to the interaction between the hot gases produced by the fire and the environment.
- Recent studies of our Team show that the fire behaviour is oscillatory, which induces a prediction error that is proportional to the average ROS.
- Sometimes the fire may assume conditions of Extreme Fire Behaviour, which are the most challenging for those who have to manage and investigate wildfires.

- The analytical model that we developed predicts the acceleration and deceleration of the fire. To be fully operational we require more data on the spread of large fires.
- For this the images obtained by space borne sensors are of great value. With them we expect to close some of the gaps that exist for the generalized application of the model.