The effect of atmospheric stability on fire-spotting in wildfire propagation

Vera Egorova[1], Gianni Pagnini[1,2], and Andrea Trucchia[1]

[1] *BCAM - Basque Center for Applied Mathematics, Alameda de Mazarredo 14, E-48009 Bilbao, Basque Country Spain*
[2] *IkerbasqueBasque Foundation for Science, Calle de María Díaz de Haro 3, E-48013 Bilbao, Basque Country Spain*

Abstract

Present research is focused on the role of atmospheric stability on wildfire propagation through its effects on fire-spotting. It appears due to the fact that wildfires produce convection columns, which are updrafts that launch firebrands into the atmosphere. These firebrands may produce new independent fire, called spot fire. This phenomenon accelerate the rate of spread of the fire and can have dangerous effects.

A mathematical model of the fire-spotting presented here is based on the Eulerian Level Set Method (LSM) with taking into account turbulence and fire-spotting, as it has been proposed in [1,2]. Thus, LSM has been extended to track random fire front. In present study, the atmospheric stability conditions are used to model the multiple fire-spotting, i.e. that the main fire can produce not only one secondary fire, but many, depending on the atmospheric conditions and wind velocity. Holding fuel type, topography, and all other meteorological factors constant, atmospheric instability promotes the spread and intensity of fires by increasing the height and strength of smoke columns and the length of firebrands' jumps.

The motion of each burning item can be random due to the effects of turbulence and fire-spotting. Thus, the random front contour can be defined by the effective indicator function [1]:

$$\phi_e(\mathbf{x}, t) = \int_S I_\Omega(\bar{\mathbf{x}}, t) f(\mathbf{x}; t|\bar{\mathbf{x}}) d\bar{\mathbf{x}}, \qquad (1)$$

where $f(\mathbf{x};t|\bar{\mathbf{x}})$ is the probability density function (PDF) that accounts for turbulence and fire-spotting effects, S is the burnt area provided by the LSM and I_Ω is an indicator function associated to the front contour generated by the LSM. Note that the point is labelled as burnt, if $\phi_e(\mathbf{x},t)$ exceeds some threshold value ϕ_e^{th}. The model is generalised by considering an ignition delay due to the pre-heating action of the hot air and to the landing of firebrands [1].

Denoting the wind velocity by U, the shape of the PDF is defined by the isotropic bi-variate Gaussian function (considering turbulence effects) $G(\mathbf{x}-\bar{\mathbf{x}};t)$ and the firebrand landing distribution $q(l)$ as follows

$$f(\mathbf{x};t|\bar{\mathbf{x}}) = \begin{cases} \int_0^\infty G(\mathbf{x}-\bar{\mathbf{x}}-l\hat{\mathbf{n}};t)q(l)dl, & \text{if } \hat{\mathbf{n}}\cdot\hat{\mathbf{n}}_U \geq 0, \\ G(\mathbf{x}-\bar{\mathbf{x}};t), & \text{otherwise.} \end{cases} \tag{2}$$

The shape of $q(l)$ is defined by a lognormal distribution as follows

$$q(l) = \frac{1}{\sqrt{2\pi}\sigma l} \exp\frac{-(\ln l/\mu)^2}{2\sigma^2}, \tag{3}$$

where μ is the ratio between the square of the mean of landing distance l and its standard deviation, σ is the standard deviation of $\ln l/\mu$. The main aim of the present study is the investigation of the role of atmospheric stability on the generation of independent secondary fires due to firebrands emissions.

In [3] authors consider the physical parametrisation of the fire-spotting. It includes only the vital ingredients, each firebrand is assumed to be spherical of the constant size. Then lognormal parameters μ and σ take the following form

$$\mu = H\left(\frac{3\rho_a C_d}{2\rho_f r g}\right)^{1/2}, \quad \sigma = \frac{1}{2z_p}\ln\left(\frac{U^2}{rg}\right), \tag{4}$$

where, according to [4],

$$H = \alpha H_{ABL} + \beta\left(\frac{I}{dP_{f0}}\right)^\gamma \exp\left(-\frac{\delta N_{FT}^2}{N_0^2}\right), \tag{5}$$

where all the parameters are defined in Table 1.

Note that in (5) the fire radiative power is the power radiated by the fire occurring within an area: $FRP = I/d$ and, therefore, it has dimension of $[MWm^{-2}]$.The wind velocity in (4) is the projection of the vector of wind to the vector Φ from some point of the computational domain to the point, where the PDF is computed. Therefore, denoting by θ the angle between

Notation	Description	Default
α	Part of ABL passed freely, $\alpha < 1$	0.24 [4]
β	$[m]$ Contribution of the fire intensity, $\beta > 0$	170 [4]
γ	Power-law dependence on FRP, $\gamma < 0.5$	0.35 [4]
δ	Dependence on stability of the FT, $\delta \geq 0$	0 [4]
H_{abl}	$[m]$ Height of the atmospheric boundary	1200
d	$[m\ ]$ Unit depth of the combustion zone	1
P_{f_0}	$[MWm^{-2}]$ Ratio of reference fire power	1 [4]
N_{FT}^2	$[s^{-2}]$ Brunt-Väisälä frequency in the FT	$2.789 \cdot 1e-4$
N_0^2	$[s^{-2}]$ Brunt-Väisälä frequency	$2.5 \cdot 1e-4$
H	$[m]$ The maximum loftable height	
ρ_a	$[kg/m^3]$ Density of the ambient air	1.1
ρ_f	$[kg/m^3]$ Density of the wild-land fuels	542
C_d	Drag coefficient	0.45
z_p	p-th percentile	0.45
r	$[m]$ Brand radius	0.015
g	$[ms^{-2}]$ Acceleration dut to gravity	9.81

Table 1: Physical parameters of the atmospheric boundary layer and fire-spotting.

wind direction and the vector Φ, expression of σ in (4) takes the following form

$$\sigma = \frac{1}{2z_p} \ln\left(\frac{(U\cos\theta)^2}{rg}\right) \geq \sigma_0, \tag{6}$$

where σ_0 is minimum possible value of σ, such that the lognormal PDF is calculated. Since θ is changing, the situation $(U\cos\theta)^2 \leq rg$ is possible, that leads to the non-positive logarithm, and, consequently, non-positive σ. In order to avoid it, θ should be bounded, such that

$$\cos\theta \geq \frac{\sqrt{rg}}{U}\exp(z_p\sigma_0). \tag{7}$$

According to the projectile motion, σ_0 is found as follows

$$\sigma_0 = \sqrt{\mu - \ln\left[\frac{U}{2g}\left(\frac{U}{2} + \sqrt{gH - \left(\frac{U}{2}\right)^2}\right)\right]}. \tag{8}$$

As one can see, (8) includes the wind speed and radius of the fire brand, as well as the height of the atmospheric boundary layer, that is changing according to atmospheric stability conditions.

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