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Numerical simulations of fire-spotting: flame characteristics formulation

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Introduction

Fire-spotting is a harmful phenomenon that accelerates the rate of the spread of fire by producing new independent ignitions by burning embers. Fire-spotting is strongly affected by wind and fire intensity, not only in transporting the firebrands, but in changing the form of the flame. Thus, the aims of this study:

- establish the relation between the flame geometry and the fireline intensity in wildfires,
- apply it to the wildfire propagation model.

Flame Geometry

Flame characteristics:

- Flame length L_f
- Flame height H_f
- Angle θ

$$H_f = L_f \sin\theta ,$$

Flame height and fireline intensity

There is an important lack in the literature on the theoretical relation between the flame height and the fireline intensity, which is a fundamental descriptor of wildfires. There are only a few attempts in this direction:

- Linear relation between Flame height and fireline intensity by Albini (1981) [1]
- Entrainment model of the flame height by Nelson Jr. et. al (2012) [2]
- Some further derivations based on these formulations

A model based on the conservation of energy

We consider an air parcel located at the top of the flame, namely at the height $z = h$, that is initially not buoyant, and it is heated by the flame. From the conservation of energy we have

$$e + PV + H - [e_0 + P_0 V_0 + H_0] = Q - W_{\mathrm{sh}} , \tag{1}$$

where

- e is the internal energy of the gas
- P and V are the pressure and the volume
- H is the mechanical energy: $H_0 = gh$, $H = g\,(h + \delta h) + w^2/2$
- Q is the heat transferred into the gas, $Q = e - e_0$
- W_{sh} is the shaft work used to move the fluid
  $W = PV - P_0 V_0 + W_{\mathrm{sh}} = -g\,(h + \delta h)$

Terms with subscript 0 refer to the initial instant and those without it to a generic instant. Plugging all the above formulae into (1) we have that the vertical velocity due to the convection above the fireline is

$$|w| = \sqrt{2gh} . \tag{2}$$

The energy flow rate in the convection column above a line of fire P_{f} that is defined as the rate at which thermal energy is converted to kinetic energy in the convection column at a specified height z:

$$P_{\mathrm{f}}(z) = \frac{gI}{c_{\mathrm{p}} T_{\mathrm{a}}} = \frac{1}{2}\rho\, w^2 |w| = \frac{1}{2}\rho\, |w|^3 . \tag{3}$$

Finally, by plugging (2) into (3) we have the following estimation of the flame height

$$\boxed{h = \left[\frac{1}{2g(\rho c_{\mathrm{p}} T_{\mathrm{a}})^2}\right]^{1/3} I^{2/3} .}$$

Fire-spotting distribution

The firebrand landing distribution $q(\ell)$ is defined by a lognormal distribution as follows

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

- μ is the ratio between the square of the mean of landing distance ℓ and its standard deviation, [3],
- σ is the standard deviation of the fire-spotting distribution improving [3],

$$\mu = H_{\max} \left(\frac{3\rho C_d}{2\rho_{\mathrm{f}}}\right)^{1/2} , \quad \sigma = \frac{1}{z_{\mathrm{p}}} \ln \left(\beta \left(\frac{2\rho_{\mathrm{f}} U^2}{3\rho C_d g L_{\mathrm{f}}}\right)^{1/2} + Fr^{1/2}\right) ,$$

where $H_{\max}$ is the maximum loftable height, ρ_{f} is the fuel density, ρ is the ambient air mass density, C_d is the drag coefficient, $Fr = U^2/rg$ is the Froude number, U is the wind velocity, r is the firebrand radius, g is the gravitational acceleration and β is some correction factor.

Results

The flame geometry changes the travel distance of the firebrand and, consequently, the parameter σ of the lognormal fire-spotting distribution, such that the following situation can be observed:

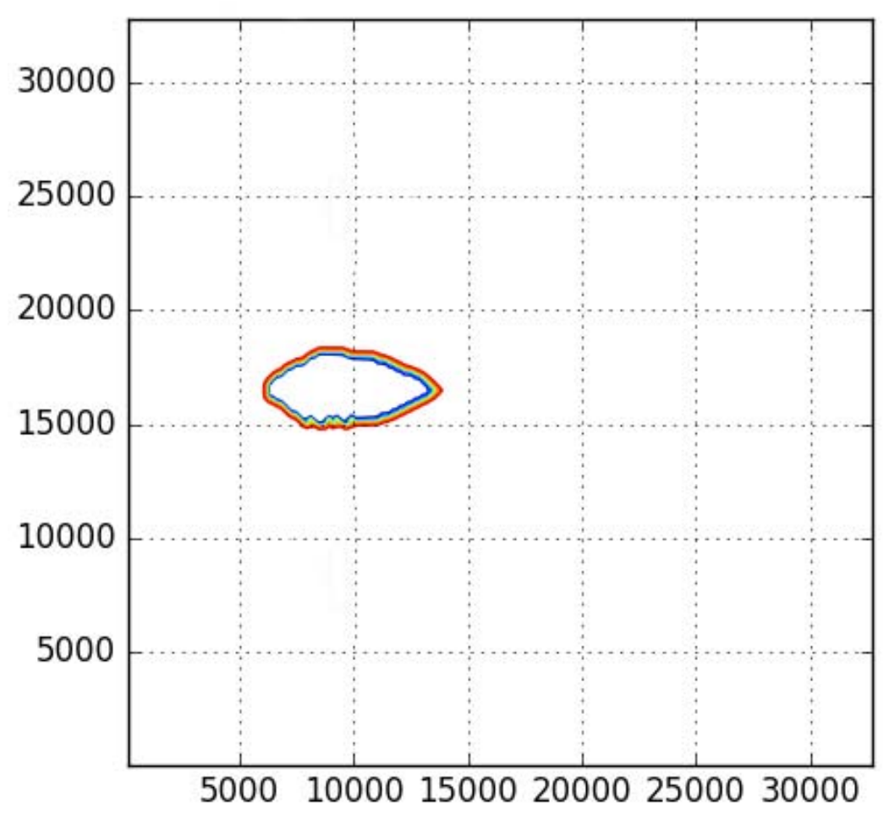

Figure: No fire-spotting: $\sigma = 8.85$

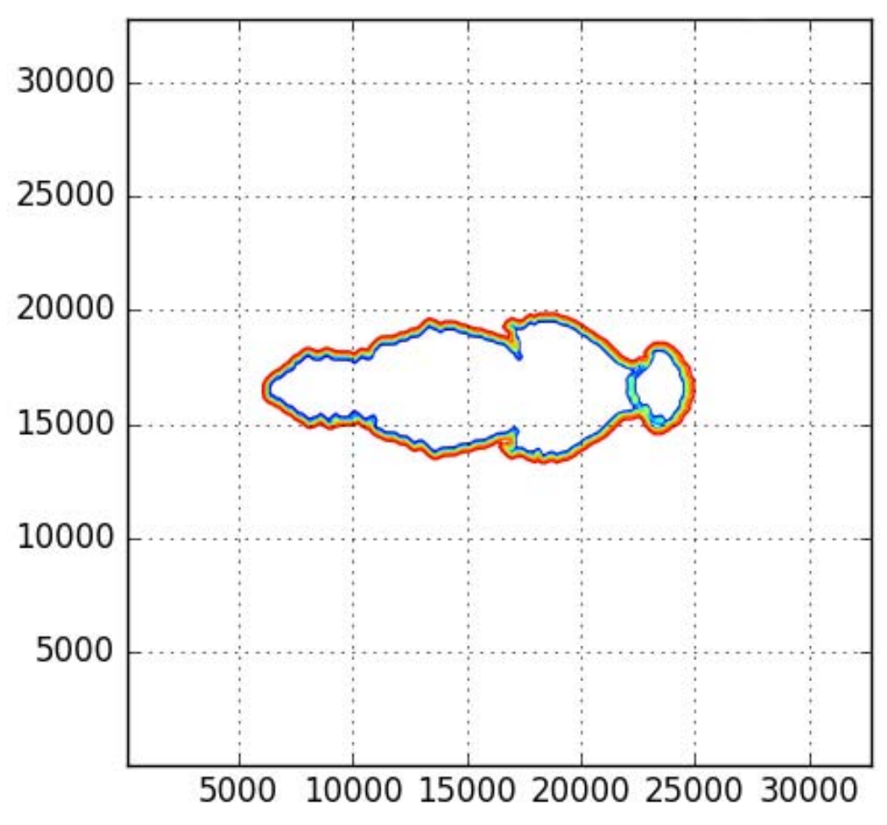

Figure: Merging of secondary fires: $\sigma = 7.74$

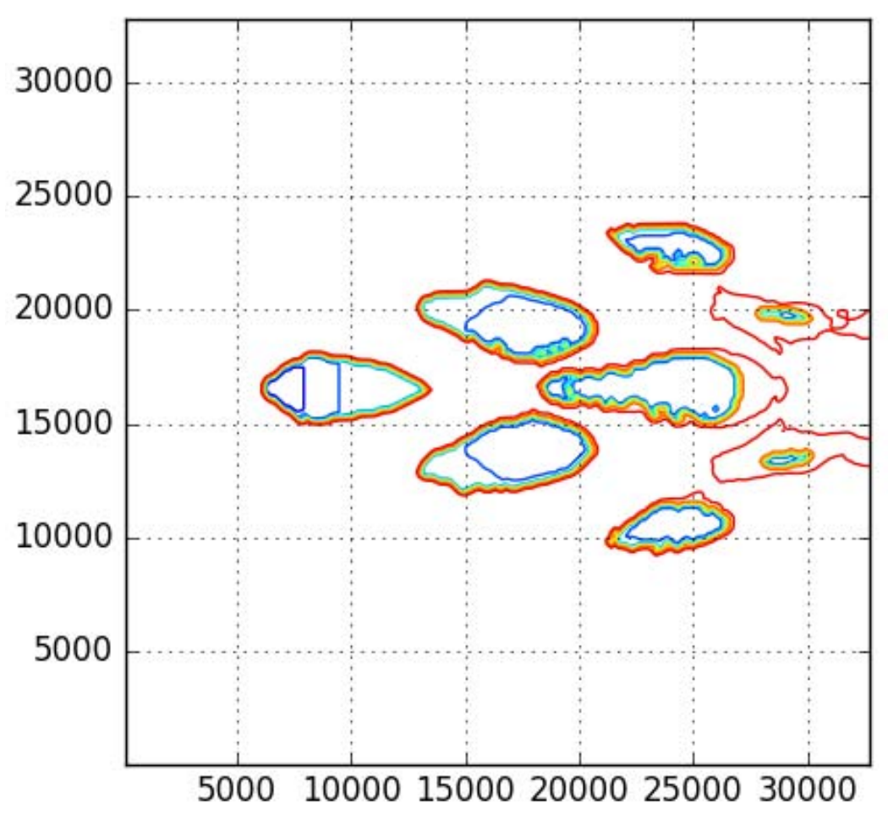

Figure: Fire-spotting: $\sigma = 8.33$

Conclusions

- The relation between the flame height and the fireline intensity is derived on the basis of the energy conservation principle and the energy flow rate in the convection column above the fireline.
- The derived formula states for the flame height a relation with the fireline intensity through the power law $2/3$.
- Derived formula is introduced into the fire-spotting model described in [3] via lognormal distribution parameters.
- The flame length affects to the parameters of the distribution and the fire-spotting.

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